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THE ACIDIFICATION OF ONTARIO LAKES:

AN ASSESSMENT OF THEIR SENSITIVITY AND CURRENT STATUS WITH RESPECT TO BIOLOGICAL DAMAGE

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THE ACIDIFICATION OF ONTARIO LAKES: AN ASSESSMENT OF THEIR SENSITIVITY AND CURRENT STATUS WITH RESPECT TO BIOLOGICAL DAMAGE

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Summary

This report describes the water chemistry of 6,000 lakes in Ontario. Trends in some water chemistry parameters are strongly correlated with acid deposition rate. Although this sample represents a small fraction of the estimated 262,000 lakes in Ontario, there are regions of the province where the lake sample is sufficiently large to allow estimates of the number of lakes at various stages of acidification to be made. Major conclusions of the report are:

- Atmospheric deposition of sulphate is the major source of sulphate in Ontario lakes, and is strongly correlated with significant reduction of pH and acid neutralizing capacity in low-ionic strength (conductivity < 50 μS) lakes.

- There are at least 19,000 lakes in Ontario estimated to have been acidified to the point (pH < 6.0) where adverse biological effects have occurred. An additional number of lakes have undoubtedly been acidified, but the subsample of smaller lakes in much of Ontario was too small to permit accurate estimation of the numbers.

- The majority of the acidified lakes (over 11,000) are in central Ontario, where total annual sulphur deposition exceeds 0.75 gS m^{-2} yr^{-1}. This deposition region includes Haliburton, Muskoka, Parry Sound, Nipissing, Timiskaming, Sudbury and Algoma.

- A large number of the acidified (7,300) lakes are in the Sudbury area, and have been acidified primarily by past sulphur emissions from the Sudbury smelters.

- There are at least 7,250 lakes in Ontario estimated to be very acidic, with all of their acid neutralizing capacity eliminated (alkalinity < 0).

- For a small subsample of watersheds in Ontario, enough data were available to permit very accurate estimations of all sizes of lakes in various stages of acidification. In these watersheds, an estimated 7,232 lakes (standard error of 308) have pH < 6.0. Of these lakes, 1978 (standard error of 37) are estimated to have alkalinity < 0.

- Acidification due to natural organic acids is not a major factor in explaining the acidification of lakes.

Sommaire

Ce rapport présente les caractéristiques chimiques de 6000 lacs en Ontario. Les tendances dans quelques paramètres chimiques sont fortement en corrélation avec le taux du dépôt acide. Puisqu'on estime qu'il y a 262000 lacs en Ontario, les 6000 lacs analysés ne représentent qu'une petite portion de ce total. Tout de même, il y a des régions dans la province où le nombre de lacs échantillonnés suffise pour estimer le nombre de lacs aux différents niveaux d'acidification. Ce rapport a conclu les points suivants:

- Le dépôt atmosphérique de sulfate contribue la plupart du sulfate aux lacs Ontariens, et est fortement en corrélation avec la réduction significative de pH et du potentiel de neutralisation de l'acide dans les lacs de basse teneur ionique (où la conductivité < 50 μS).

- On estime qu'il y a au moins 19000 lacs en Ontario qui sont si acidifiés qu'ils ont subi des effets biologiques adverses (pH < 6.0). Sans doute, il y a plus des lacs qui sont acidifiés mais le sous-échantillon de plus petits lacs n'était pas suffisant pour estimer ce nombre plus exactement.

- Le plus grand nombre des lacs acidifiés (plus que 11000) sont dans la région centrale de l'Ontario, où le dépôt total annuel de sulfate surpasse 0.75 g S m^{-2} yr^{-1}. Cette région de dépôt comprend Haliburton, Muskoka, Parry Sound, Nipissing, Timiskaming, Sudbury et Algoma.

- Un grand nombre des lacs acidifiés (7300) sont dans la région de Sudbury, et sont acidifiés principalement par les émissions historiques d'anhydride sulfureux des fonderies de métaux non-ferreux à Sudbury.

- On estime qu'il y a au moins 7250 lacs en Ontario qui sont très acidifiés et qui ont perdu tout leur potentiel de neutralisation de l'acide (alcalinité < 0).

- Pour un petit nombre des bassins hydrographiques en Ontario, les données suffisent à faire des approximations très exactes des lacs de toutes grandeurs aux différents niveaux d'acidification. Pour ces bassins, on estime que 7232 lacs (écart-type de 308) ont un pH < 6.0. De ces lacs, on estime que 1978 (écart-type de 37) ont une alcalinité < 0.

- Le rôle des acides organiques naturels n'est pas important pour l'acidification des lacs.

Acknowledgements

The acquisition and organization of data in this report are the result of the efforts of many people. The authors would like to gratefully acknowledge the contributions of Donna Wales and Doug Dodge of the Ministry of Natural Resources, Bill Keller, Len Maki, Dave Hollinger, Reg Genge, Jan Beaver, Ron Reid, and Bob Girard of the Ministry of Environment. Data collected from surveys conducted by Harold Harvey of the University of Toronto, Jim Kramer of McMaster University, and John Kelso of the Department of Fisheries and Oceans are included in this report. The assistance of Sheryl Gleave in typing (and re-typing) this report is gratefully acknowledged.

1. Introduction

The Ontario Acid Sensitivity Database (OASD) is a compilation of chemical data collected on about 6000 lakes in Ontario. These data were derived from a number of studies, most of them conducted as part of the Acid Precipitation in Ontario Study (APIOS). Prior to these surveys, little was known about the geographic distribution of water chemical parameters in Ontario. Some rudimentary information was available as part of data collected by the Ontario Ministry of Natural Resources' (MNR) aquatic habitat surveys, but the chemical data were usually obtained using field analytical kits by personnel unskilled in analytical chemistry, and were considered to be semi-quantitative. Some fundamentals were known: lakes on the Canadian Shield were primarily softwater, lakes in the Clay Belt and in areas of calcareous sedimentary rock were hardwater, and there were acidic lakes in the vicinity of smelting and sintering operations in Sudbury and Wawa (Beamish and Harvey, 1972; Somers and Harvey, 1984). Other than these general observations, data were only available on specific lakes from detailed studies conducted by university or Ministry of the Environment (MOE) researchers, and most of these studies were related to lake eutrophication or metal contamination. Exceptions were several surveys conducted by the Ministry of the Environment's northeastern region. These surveys were designed to delineate the extent of the Sudbury acidification zone (Conroy *et al.* 1978; Pitblado *et al.* 1980; Keller *et al.* 1980).

The first evaluation of the extent and magnitude of the acidification problem in Ontario was conducted in 1980 (MOE 1980). Several other compilations of these and other data were made (MOE 1981,1982,1983, MNR 1987) and parts of these data have been published elsewhere (Jeffries 1986, Neary and Dillon 1988). This report provides an update of the acid sensitivity data on lakes in Ontario, documents the analytical methods and data sources, and provides estimates for some areas of the province of the total number of lakes in various pH and alkalinity classes, which are interpreted in terms of the aquatic resources at risk in the province. Finally, the number of lakes in which the aquatic biota have been deleteriously affected is estimated.

2. Data Sources

Most of the data were collected as part of the Aquatic Effects Programme of APIOS, but data from universities and other government agencies were included provided that similar analytical methods were used. It was a prerequisite that Gran titration alkalinity (equivalence-point titration) rather than a fixed-endpoint titration alkalinity be measured. This effectively eliminated all but a few data sets collected before 1979. A brief description of each survey with a discussion of known lake sampling biases is included in Table 1.1.

2.1 Lake Surveys in the Data Base

2.1.1 Ministry of the Environment Studies

Data on 2912 of the lakes are derived from studies carried out by various groups within MOE. These include:

Northwestern Region - Data for 649 lakes from annual surveys conducted between 1980 and 1988. Chemical analyses were conducted at MOE laboratories at Thunder Bay and Toronto. The two most recent surveys (1987 and 1988; each with 100 lakes) covered large areas of the province with no previously measured lake water chemistry. These lakes were selected in a randomized design within lake size strata. Other surveys were focused on the vicinity of the Atikokan generating station, and in the Pukaskwa Park area. Data on 589 of the lakes include major anions and cations. Overall, however, the sample from the northwest is biased strongly to large lakes (median size = 188 ha).

Northeastern Region - Data are available on 928 lakes in the Northeast. Most of the lakes are south of latitude 50°, and many of the surveys were conducted within the Sudbury acidification zone (defined in Section 6.5). Annual 'random lake' surveys were conducted within the region from 1979 to 1984, with periodic reassessments of over 200 lakes ongoing. Samples were analyzed at the MOE labs in Rexdale and Thunder Bay, and complete anion and cation data are available for 414 of the lakes. Overall, the sample is biased toward large lakes, with the median lake size being 70 ha. Over 200 of the lakes

Table 2.1 Summary of data sources, and criteria for, and known biases in, lake selection.

Source	Date	n	Criteria	Bias
<u>ONTARIO MINISTRY OF THE ENVIRONMENT</u>				
<u>Northwest Region</u>				
APIOS Surveys	1979-84	330	- fixed-wing aircraft - no previous data - no carbonate geology areas included (based on bedrock maps)	- no very small (< ~ 25 ha) lakes - no very insensitive lakes
Atikokan Survey	1979-84	200	- most lakes in a 50 km radius of Marmion Lake generating station - includes helicopter access for small lakes	- no known size or sensitivity bias
Pukaskwa Survey	1981	20	- includes helicopter access for small lakes - all lakes in specified area	- no known size or sensitivity bias
Thunder Bay Survey	1979-80	100	- fixed-wing aircraft - insensitive (carbonate) areas excluded based on bedrock maps	- no small lakes - no very insensitive lakes
Kenora Survey	1981-82	75	- fixed-wing aircraft - insensitive (carbonate) areas excluded based on bedrock maps	- no small lakes - no very insensitive lakes

Table 2.1 (Cont'd)

Source	Date	n	Criteria	Bias
Red Lake Survey	1987	98	- fixed-wing and helicopter access - lakes chosen randomly within area size strata	- no known size or sensitivity bias
Ignace/ Sioux Lookout Survey	1989	99	- fixed-wing and helicopter access - lakes chosen randomly within area size strata	- no known size or sensitivity bias
<u>Northeast Region</u>				
APIOS Surveys	1979-84	~400	- random lake selection in the region - reasonable access	- none known
Sudbury Environmental Study Survey	1980, 1985	320	- fixed-wing aircraft or road access - all different bedrock geologies represented, lakes chosen at random from within types	- no small lakes
Intensive Lake Study	1979-88	29	- 6 samples per year	- none known
Lakeshore Capacity Study Survey	1979-80	43	- substantial cottage development (good access)	- no very small lakes

Table 2.1 (Cont'd)

Source	Date	n	Criteria	Bias
Remote Sensing Survey	1986	210	- all lakes visible in two LANDSAT images	- none known
Sudbury Area Lake Trout Lakes	1980	38	- known lake trout lakes	- no small or shallow lakes - no lakes with major acidification effects
<u>Central Region</u>				
APIOS Surveys	1980-82	123	- recreational lakes, good access	- very small lakes under represented
MOE/MNR Combined Study	1979	22	- not known	- primarily large lakes
<u>Southeast Region</u>				
APIOS Surveys	1980, 1987, 1988	629	- random selection, independent of lake size or geology	- none known, but reliance on fixed wing aircraft in some years resulted in few small lakes in some areas

Table 2.1 (Cont'd)

Source	Date	n	Criteria	Bias
Red Lake Survey	1987	98	- fixed-wing and helicopter access - lakes chosen randomly within area size strata	- no known size or sensitivity bias
Ignace/ Sioux Lookout Survey	1989	99	- fixed-wing and helicopter access - lakes chosen randomly within area size strata	- no known size or sensitivity bias
<u>Northeast Region</u>				
APIOS Surveys	1979-84	~400	- random lake selection in the region - reasonable access	- none known
Sudbury Environmental Study Survey	1980, 1985	320	- fixed-wing aircraft or road access - all different bedrock geologies represented, lakes chosen at random from within types	- no small lakes
Intensive Lake Study	1979-88	29	- 6 samples per year	- none known
Lakeshore Capacity Study Survey	1979-80	43	- substantial cottage development (good access)	- no very small lakes

Table 2.1 (Cont'd)

Source	Date	n	Criteria	Bias
Dorset Research Centre				
Limnology Section Intensive Study Lakes	1979-Present	~70	- many selected because of recreational importance	- none known
Limnology Section Surveys	1980, 1984, 1988	450	- many of the surveys include all lakes in a geographic zone (a watershed, or a township)	- none known
ONTARIO MINISTRY OF NATURAL RESOURCES				
Regional Surveys	1979-81	1063	- good sports fishery	- large lakes over-represented - bias to good water quality able to support good fish populations
Algonquin Survey	1982-83	811	- all lakes in a large region (defined by watershed boundaries) of Algonquin Park and surrounding areas	- none known
Parry Sound Survey	1985	~500	- all lakes in specific watersheds	- none known

Table 2.1 (Cont'd)

Source	Date	n	Criteria	Bias
DEPARTMENT OF FISHERIES & OCEANS				
National Inventory	1980	178	- survey of headwater lakes across Ontario	- headwater lakes only
Sudbury, Parry Sound Survey	1982	45	- all lakes in specific watersheds	- none known
UNIVERSITY STUDIES				
Kramer	1979	64	- Quetico-Atikokan region - canoe route access or road access	- few small lakes
Zimmerman and Harvey	1979	340	- province-wide - road access - insensitive areas excluded	- few small lakes

were sampled as part of a research project to determine the feasibility of using remote sensing to determine the acidification status of lakes (Pitblado,1988). The lakes were selected from two discrete areas, one in Algoma and the other in Sudbury, and they represented all lakes visible to LANDSAT (> 1 ha) within those areas. These two surveys contain most of the smaller lakes in the data set from the northeast region.

Central Region - Data on 123 lakes in central Ontario from surveys completed in 1980, 1981, and 1982. 68 of the lakes have complete anion and cation data, while 55 have pH, alkalinity, and conductivity only. All analyses were performed at the MOE Rexdale laboratories. Lake selection was biased towards those used for recreation, so the median lake size is a little large (39 ha) to be representative of the distribution of lake sizes in this area of the province.

Southeastern Region - Data on 627 lakes in southeastern Ontario, both on and off the Shield. Most of the data comes from surveys conducted in 1981, 1983 and 1988. Most of the lakes (433) have pH, alkalinity, and conductivity data only. Samples were analyzed in the MOE labs at Kingston and Rexdale. These surveys were random, and included both large and very small lakes. The median lake size of 19.5 ha makes these data the most representative of any of the regional surveys. Surveys in 1987 and 1988 were specifically designed to obtain complete water chemistry from smaller lakes in the region.

Dorset Research Centre - 520 lakes in central Ontario were sampled by staff of the Limnology Section, Dorset Research Centre. Some data are from lakes studied much more intensively as part of the chemical studies of APIOS, and some data are from lakes being studied under other programmes. Most samples were taken in surveys in 1980, 1984, and 1988. Almost all (491) of the lakes have complete anion and cation data. Samples were all analyzed at the MOE labs in Dorset or Rexdale. The median size of the lakes is 26 ha, which is slightly skewed toward larger lakes.

MOE/MNR Combined studies - There are two joint studies with lake information represented in the data base. One is a set of 35 lakes in the Sudbury area sampled in 1980. The median lake size is 55 ha. Since all of these lakes either support or used to

support lake trout populations, the lakes tend to be larger and deeper than most lakes. The other is a set of 18 larger lakes from central Ontario (median of 80 ha) which were evaluated as part of a selection process for lakes to be studied more intensively for fisheries. All of these lakes have relatively complete water chemistry, and the samples were analyzed at the MOE laboratories in Rexdale.

2.1.2 Ministry of Natural Resources Studies

A total of 2540 lakes in the data base have been sampled by the Ministry of Natural Resources. These surveys include:

Regional Surveys - Various sampling programmes conducted by MNR Regions and Districts between 1979 and 1981 yielded data for 1058 lakes. Lake selection was biased towards lakes with known or suspected sports fisheries and was strongly skewed to larger lakes (median size 86 ha). Many lakes were drawn from the OFIS (Ontario Fisheries Information System) data base, which includes fish presence/absence information. The chemical data include only pH, alkalinity, and conductivity with the pH and conductivity determined in the field with portable meters.

Fisheries Branch Acidification Programme - Data are included for 1467 lakes surveyed between 1982 and 1985 as part of the acidification programme of the Ministry of Natural Resources. These surveys included specific studies where all lakes greater than 5 hectares within a tertiary watershed were analyzed. Samples were mostly taken through the ice as a 5 m composite, and were analyzed at the MOE labs in Dorset or Rexdale. Data include pH, alkalinity, conductivity, colour, DOC, metals, and all major cations and anions except chloride. Overall, the median lake size of 34 ha makes the collection slightly skewed toward larger lakes, although data are available for many small lakes.

Algoma Fisheries Assessment Unit - Data on 5 large lakes (median size 111 ha) was obtained from the MNR Algoma Fisheries assessment unit. Data on major anions and cations are available. Conductivity and pH were determined with field meters.

2.1.3 University Studies

University of Toronto (Zimmerman and Harvey 1979) - Data were obtained in 1978 from 298 lakes in both low and high acid deposition areas. Conductivity and pH were determined by portable meters (Sargent-Welch PBL and Barnstead PMC-51, respectively), and Gran alkalinity was measured by titration in a field laboratory. Although a wide range of lake sizes were sampled, the sample is skewed toward larger lakes (median 68 ha). The lakes were selected based on the data in the Ontario Fisheries Information System . From that data base, lakes with low pH and total dissolved solids were selected, with an emphasis on any headwater lakes. Areas of Ontario known to have mostly hardwater lakes were avoided, introducing a bias toward softwater lakes. Since the original OFIS data base is strongly biased toward large lakes supporting important fisheries, this bias was also carried over to the subset selected by Zimmerman and Harvey.

McMaster University (Kramer, 1979) - Study lakes were located in the Quetico-Atikokan region. This region was identified as having low alkalinity in a 1977 survey. Tube composite (6 m depth) or 1 m "grab" samples from 55 lakes were taken in the summer of 1978. The survey is strongly biased toward large lakes (median size 96 ha). Conductivity and pH were determined by field measurements, with the pH verified on a subset of the lakes by laboratory analysis. All alkalinities were determined in a field laboratory by Gran titration.

2.1.4 Federal Government Studies

Department of Fisheries and Oceans (DFO) National Inventory - data from a survey of 176 headwater lakes across Ontario. Chemical analyses were conducted by Environment Canada. The lakes were all headwater lakes, and the median lake size was small (4.5 ha). Lake selection methodology and details of analytical methods are described in Kelso *et al.* (1986). Major cation and anion data, with the exception of potassium, are available for all of the lakes. Sulphate was analyzed colorimetrically (methylthymol blue), atypical to the other surveys represented here.

DFO Ontario Survey - 41 lakes in the Sudbury area of Ontario were sampled in 1982. Cation and anion analyses were performed by Environment Canada. The median lake size was 11 ha, and the sample represented all of the lakes greater than 1 ha in one river system (the Mahzenazing River).

2.2 Data Available

As described above, there is not always consistency in the number of chemical parameters for each lake. In some of the earlier surveys, only pH, alkalinity, and conductivity were measured. Later surveys have usually measured all of the major cations and anions, as well as nutrients and selected metals. The number of lakes with data for each parameter is shown in Table 2.2.

2.3 Representativeness of the Sample

2.3.1 Geographic Extent of the Sample

The exact number of lakes in Ontario is unknown. Further, there is no consensus about what constitutes a lake. For the purposes of this report, the term 'lake' is taken to be a non-ephemeral water body greater than or equal to 1 ha in size. A very small number of water bodies less than 1 ha are represented in the OASD.

The best estimate of the number of lakes in Ontario can be found in Cox (1978), who attempted to measure and enumerate all of the lakes. Although Cox enumerated water bodies less than 1 ha in size in some areas of the province, the results excerpted here are only for water bodies greater than or equal to 1 ha in size. Even at that size, lakes could not be directly enumerated from available topographic maps because much of northern Ontario had been mapped at a minimum scale of 1:250,000. At that scale, lakes less than 10 ha are not mapped.

Table 2.2: Number of lakes with measurements made for each parameter of interest. The total number of individual lakes included in the OASD is 6000.

	Parameter	Number of Lakes
Physical Data:		
	Lake Area	6000
Chemical Data:		
	pH	5982
	Gran Alkalinity	5911
Cations:	Calcium	3702
	Magnesium	3591
	Sodium	3304
	Potassium	3145
Anions:	Sulphate	3599
	Chloride	996
	Nitrate	377
Other:	Conductivity	5617
	Colour (apparent)	2066
	Colour (true)	605
	Dissolved Organic Carbon	2581
Metals:	Aluminum	3264
	Iron	1267
	Manganese	2952

Cox developed 2 methods for estimating the number of lakes in the 1-9.9 ha range, based on the distribution and numbers of larger water bodies. To estimate the number of lakes in the 1-9.9 ha size range, we have taken as the population of lakes in the northern watersheds the most conservative of the estimates made by Cox.

The location of lakes in this sample are unevenly distributed throughout the province (Figure 2.1). This is in part due to the biases in the various surveys discussed in Section 2.1, and partly due to the remote nature of many of the northern lakes.

2.3.2 Size Distribution of Lakes in the Sample

Cox estimated that there were 262,762 lakes in Ontario greater than 1 ha in size (excluding the Great Lakes). The size distribution of the lakes in the province is shown in Table 2.3, along with the number of lakes in the OASD in each size category. The lake size distribution represented in the OASD is skewed strongly to larger lakes, ranging from less than 1 percent of lakes in the 1-9.9 ha range to 37 percent of the lakes greater than 1000 ha. This is primarily due to bias built in to the sampling design, where lakes with known sport fisheries being more likely to be sampled than lakes with unknown fishery status. In Ontario, the lakes that have been assessed for fisheries tend to be the larger lakes. There were, however, several surveys which attempted to collect data representative of all lake sizes. As a result, some individual watersheds have good representation in all size ranges.

Based on these numbers, pH data are available for 2.29% of the estimated number of lakes greater than 1 ha in the province (see Appendix A).

Table 2.3: Size distribution of lakes Ontario and of those sampled in this study

Lake Size Range	Ontario Total	Number Sampled	%
< 1 ha	?	39	?
1-9.9 ha	170668*	1011	0.59
10-99 ha	81426	2913	3.59
100-999 ha	9771	1701	17.53
> 1000 ha	897	375	37.68
Total	262762	6000	2.29

* estimated by Cox (1978)

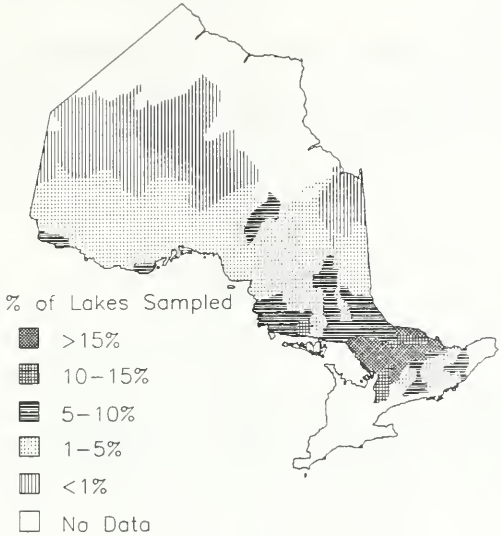

Figure 2.1: Percent of lakes sampled in different parts of Ontario. Data are grouped by tertiary watershed.

2.3.3 Sample Date

The lakes in this data base were sampled between 1976 and 1989 with the most lakes sampled in 1980 and 1981. The number of lakes sampled in each year is shown in Fig. 2.2. February is the month with the most lakes sampled; a histogram with the month of sampling is shown in Figure 2.2. The influence of sample collection time can be quite marked in smaller lakes, particularly for pH and alkalinity (Jeffries et al., 1979, Stoddard, 1987). Because only a very small number of lakes were sampled more than once, this effect is not considered here.

2.3.4 Sample Type

Because this database results from a compilation of data collected as part of many studies, there were different sampling methods used. The vast majority of the samples were composite (unweighted) samples collected to either 5 m or a lesser depth in the case

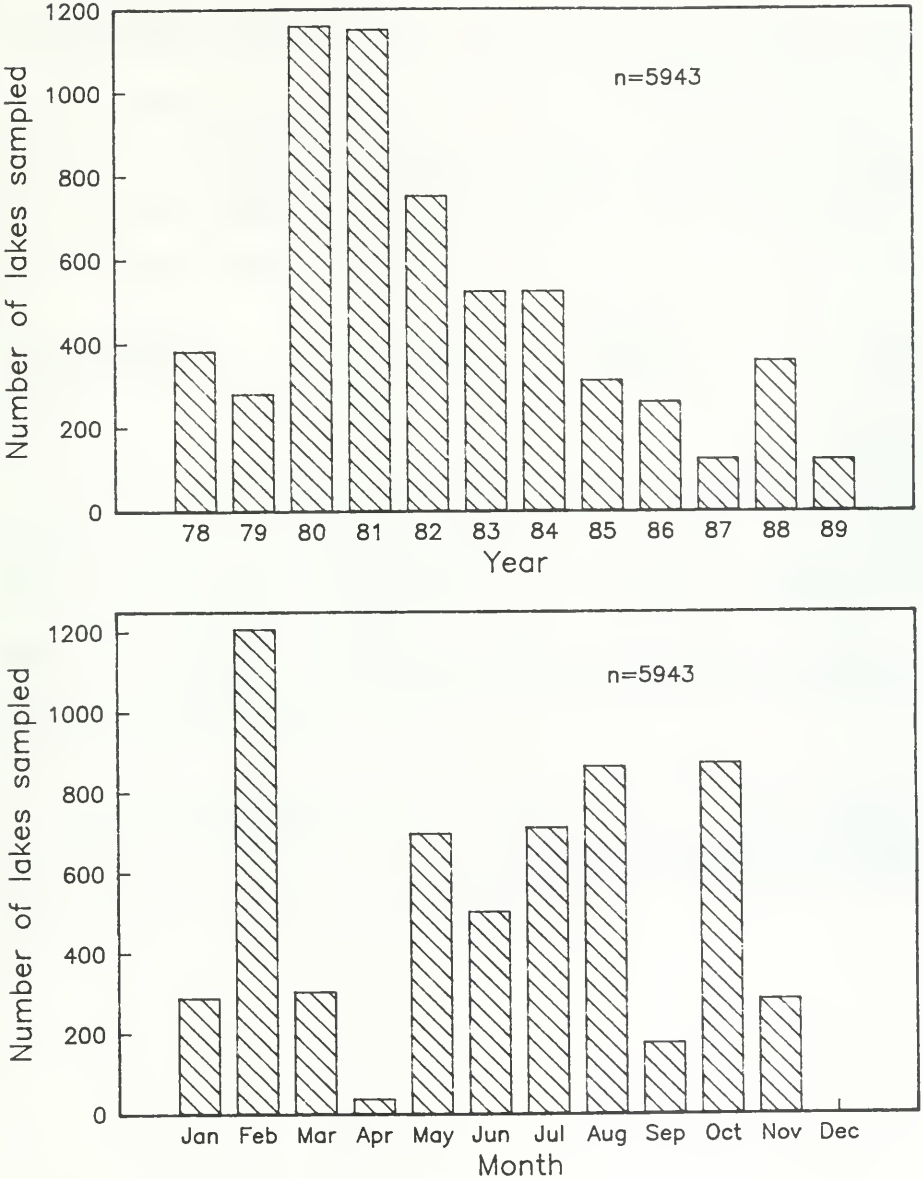

Figure 2.2 Distribution of lakes by year (top) and by month of year (bottom) sampled. There are 57 lakes included where the sampling time is not known.

of very shallow lakes < 6 m deep. The various sample types, and the number of lakes sampled using each method, are given in Table 2.4.

Table 2.4: Sample type and sampling season of lakes in database

Season	5 m unweighted composite	subsurface sample[2]	epilimnetic unweighted composite[3]
Ice Cover (December - April)	1819	19	0
Spring Overturn (May)	578	124	2
Summer Stratified (June - September)	2206	40	0
Fall Overturn (October - November)	1134	19	2
Total[1]	5737	202	4

[1] unrecorded = 57
[2] collected just below the lake surface
[3] variable depth depending on thermal regime

3. Measured Lake Chemistry

Five laboratories were involved in the measurement of the chemical parameters described below. The analytical methods used for each of the parameters are described in Appendix C. For each parameter, a histogram of measured values is presented. The value ranges with the upper end of the range inclusive. For example, the pH range 6.0 to 6.5 represents lakes with pH > 6.00 and pH ≤ 6.50.

3.1 Cations

3.1.1 pH

As discussed in Appendix C, measured pH was either laboratory determined on a non-degassed sample, or determined in the field with a pre-calibrated portable meter. Lake pH ranged from slightly over 3.0 in an acid mine drainage lake to a maximum of 9.8 in a productive hardwater lake sampled in July. The mean lake pH was 6.69 (median=6.68). Expressed as a cation concentration, hydrogen ions are a minor water constituent (less than 1% of the total cation concentration on average). The distribution of pH values is shown in Figure 3.1.

Biological damage appears to begin at approximately pH 6.0 (RMCC 1989). Of the total number of lakes sampled, 1150 had pH less than or equal to 6.0 (19.2%). This is discussed in detail in Section 8.1. There are several factors which influence the pH of a lake, and these factors will be discussed further in Section 6.

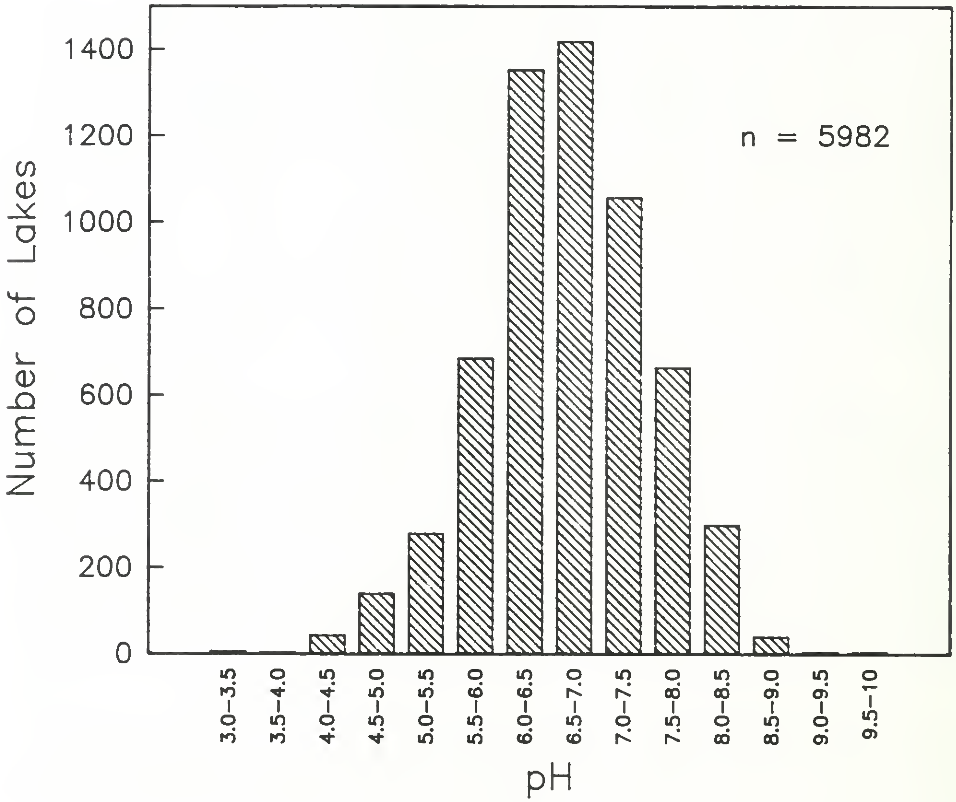

Figure 3.1: Distribution of pH in Ontario lakes.

Table 3.1: Statistical summary for pH and base cations ($\mu eq\ L^{-1}$)

	pH	Ca	Mg	Na	K
n	5982	3702	3591	3304	3153
Mean	6.69	373	49	48.7	13.1
Minimum	3.03	5	44.4	4.4	1.0
Maximum	9.80	3523	1956	1956	76.2
First Quartile	6.16	127	26	26.4	9.0
Median	6.68	175	35	35.2	11.8
Third Quartile	7.25	376	46	46.1	15.6
Std. Deviation	0.83	462	89	89.3	6.9
Skewness	0.18	2.52	12.3	12.3	2.24
Kurtosis	0.13	6.73	190	189	9.7

3.1.2 Calcium

Calcium is the dominant cation in Ontario lakes, constituting on average 59.2 % of the total cations in solution. The concentration of calcium in lake water is highly variable, ranging from 5 to over 3500 microequivalents. The distribution is highly skewed to lower values (see Figure 3.2), with 80 % of the lakes having calcium concentrations less than 500 $ueq.L^{-1}$. There are data from 153 lakes with calcium concentrations between 1500 and 3523 $\mu eq.L^{-1}$ not shown on Figure 3.2.

3.1.3 Magnesium

Magnesium is the second most important cation in Ontario lakes, constituting an average of 24.7 % of the total cations in solution. Its concentration is highly correlated to that of calcium (r^2=0.81), with an average molar ratio of 2.68:1 Ca:Mg (Figure 3.3). Like calcium, the sample of Ontario lakes represented in this data base is strongly skewed to lower values (see Figure 3.4). There are data from 20 lakes between 1000 and 1595 $\mu eq.L^{-1}$ not shown on Figure 3.4.

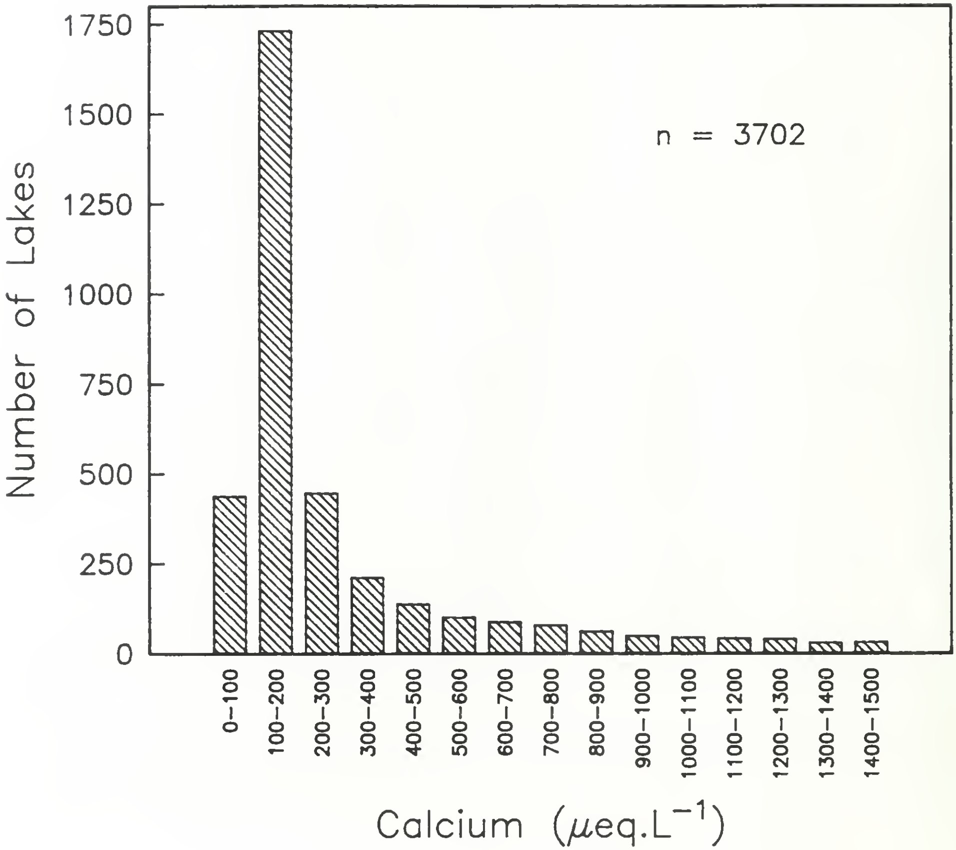

Figure 3.2: Distribution of calcium in Ontario lakes.

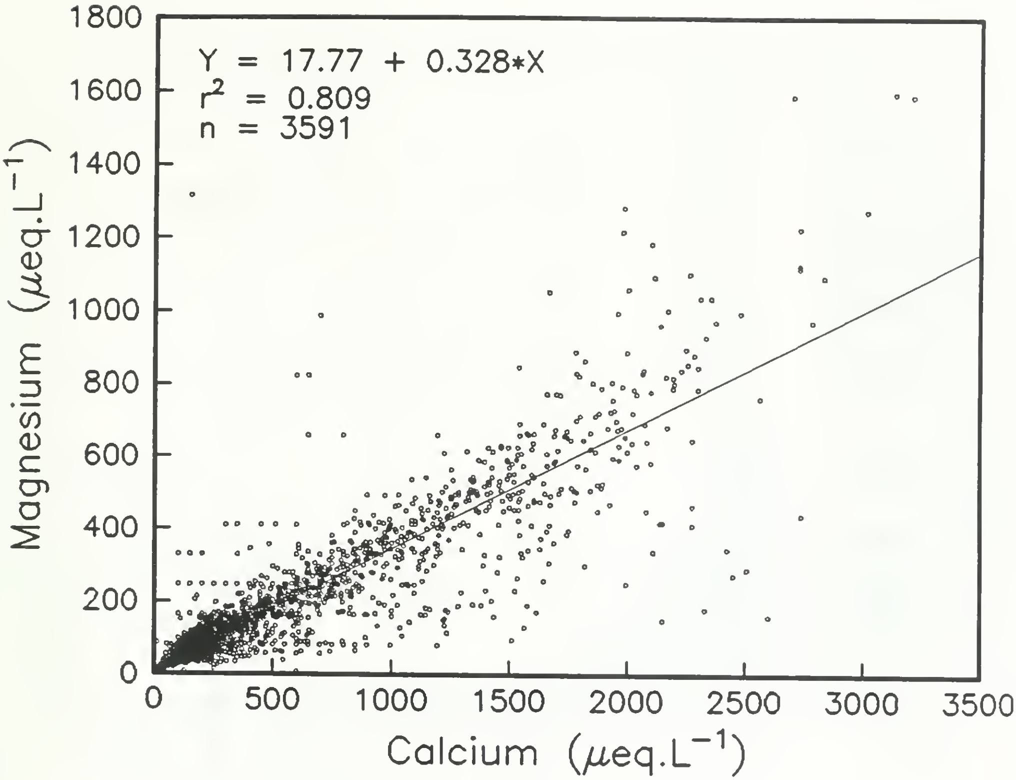

Figure 3.3: The relationship between calcium and magnesium in Ontario lakes.

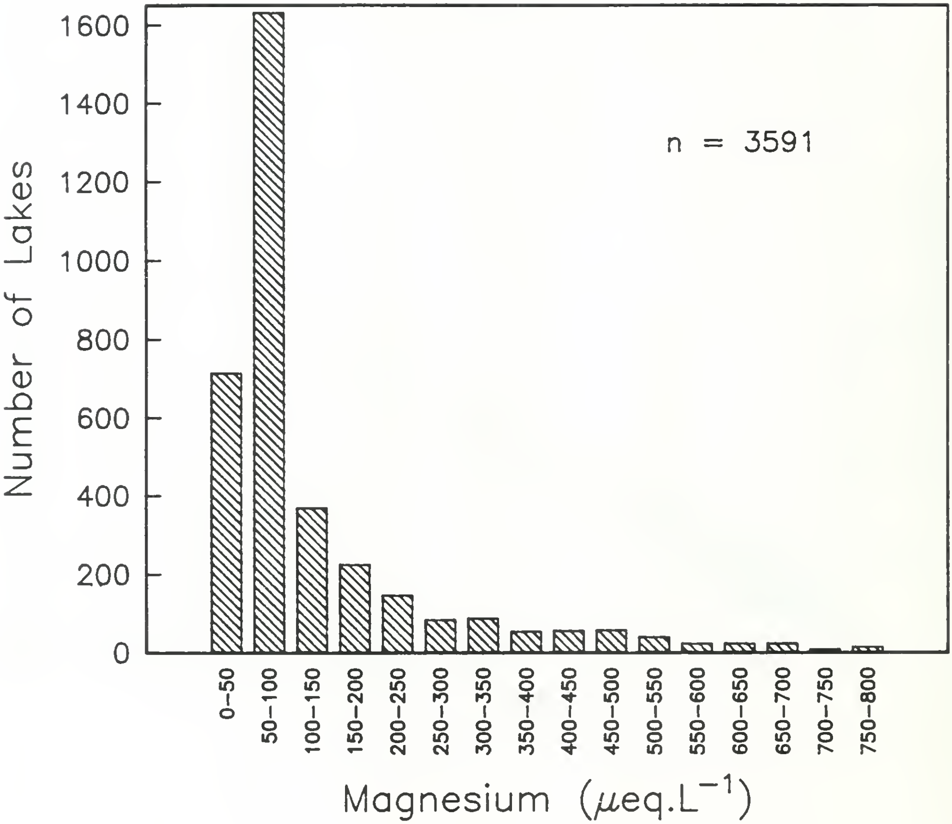

Figure 3.4: Distribution of magnesium in Ontario lakes.

3.1.4 Sodium

There are apparently two sources of sodium in Ontario lakes: natural and anthropogenic. The vast majority of the lakes have low sodium levels (median = 35 $\mu eq.L^{-1}$), but there is a number of lakes where sodium values exceed this significantly. All of these lakes are in the vicinity of roads which receive road salt for de-icing during the winter. In these lakes, the sodium values are highly correlated with chloride concentrations (Figure 3.5). On average, sodium comprises 11.6% of the cations in solution, but it can be the dominant cation if there is a road salt influence. The distribution of sodium concentrations in Ontario lakes is shown in Figure 3.6, with data from 8 lakes with sodium concentrations between 1000 and 1956 $\mu eq.L^{-1}$ not shown.

3.1.5 Potassium

Potassium is present in low levels in all of the lakes, but is a minor cation in solution (average 3.6 %). The concentration of potassium is not correlated to any of the other cations in solution, and its distribution is less skewed than the other cations (Figure 3.7).

3.2 Anions

3.2.1 Alkalinity

Alkalinity is a measure of the total amount of acid neutralizing substances in water. Over most of the pH range of lakes in this database, it is predominantly a measure of the bicarbonate anion in solution. In calcareous areas, the bicarbonate anion is produced during natural weathering or congruent dissolution. In this database, the Gran alkalinity is correlated with calcium ($r^2 = 0.963$, Figure 3.8). Unlike the other chemistry parameters, Gran alkalinity can be negative. When less than zero, it is a measure of the mineral acidity of the solution. 4.6 % of the lakes had negative Gran alkalinities. On average, bicarbonate constitutes 41.5% of the anions in solution. The distribution of alkalinity is shown in Figure 3.9, except for data from 34 lakes with alkalinities between 3000 and 5850 $\mu eq.L^{-1}$.

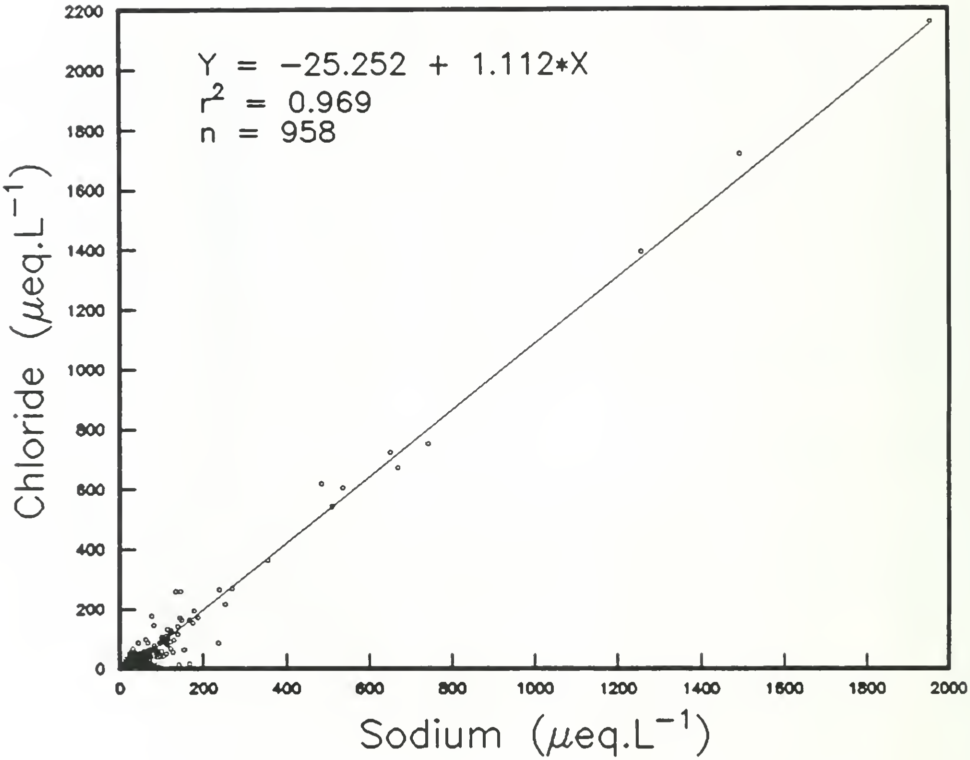

Figure 3.5: The relationship between sodium and chloride in Ontario lakes.

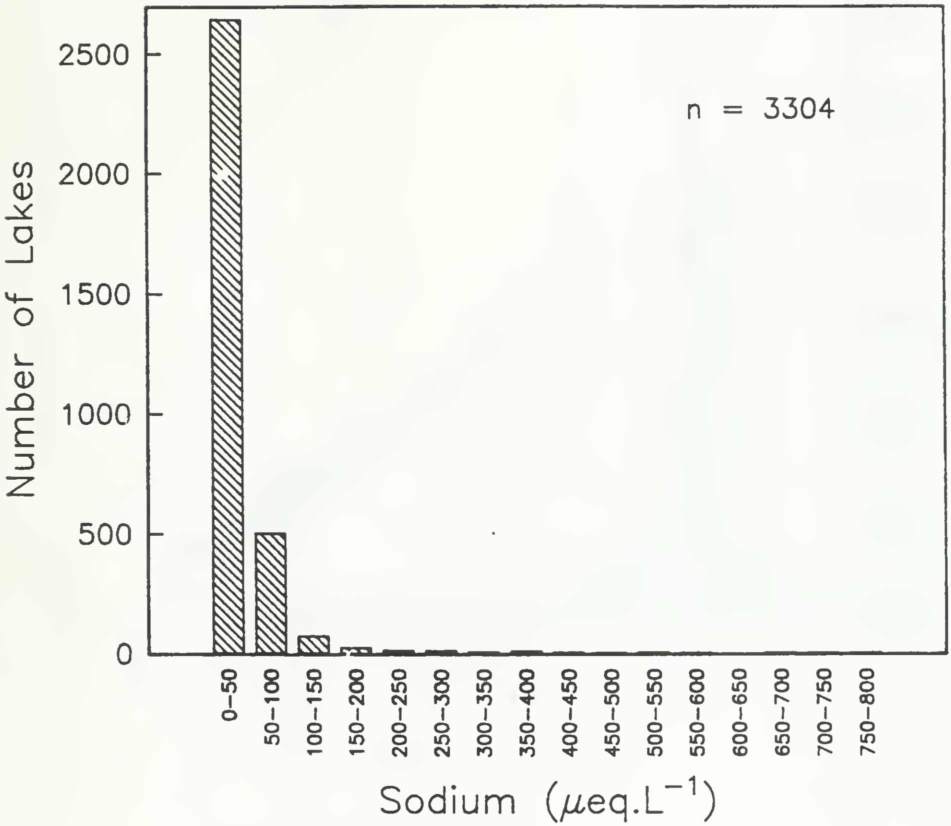

Figure 3.6: Distribution of sodium in Ontario lakes.

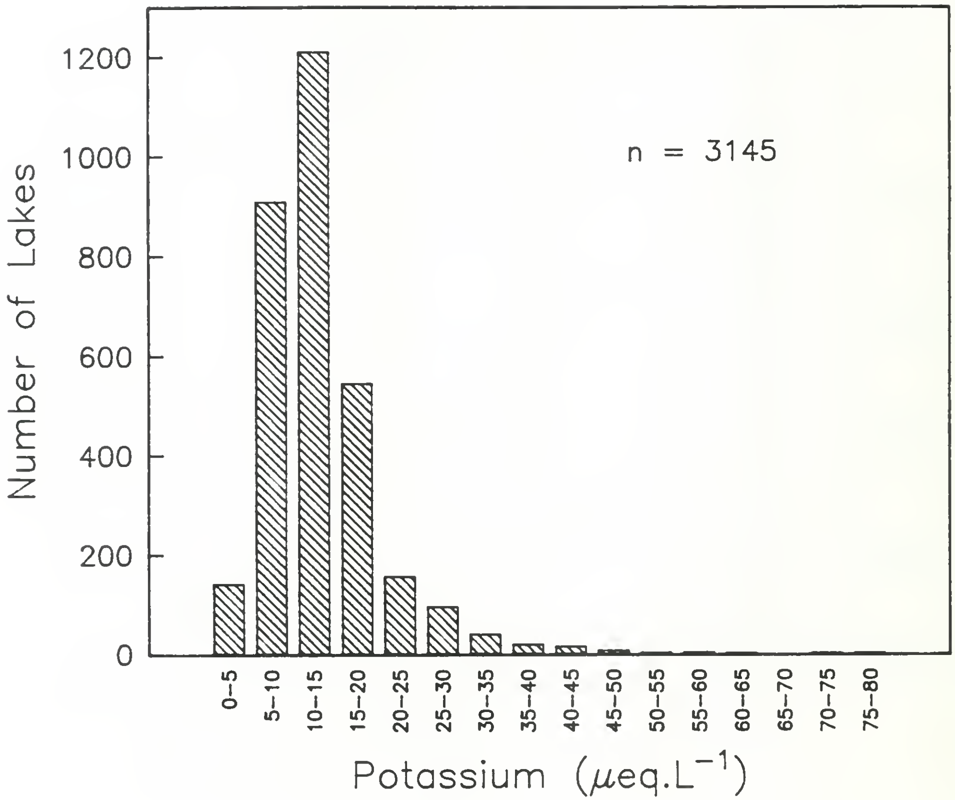

Figure 3.7: Distribution of potassium in Ontario lakes.

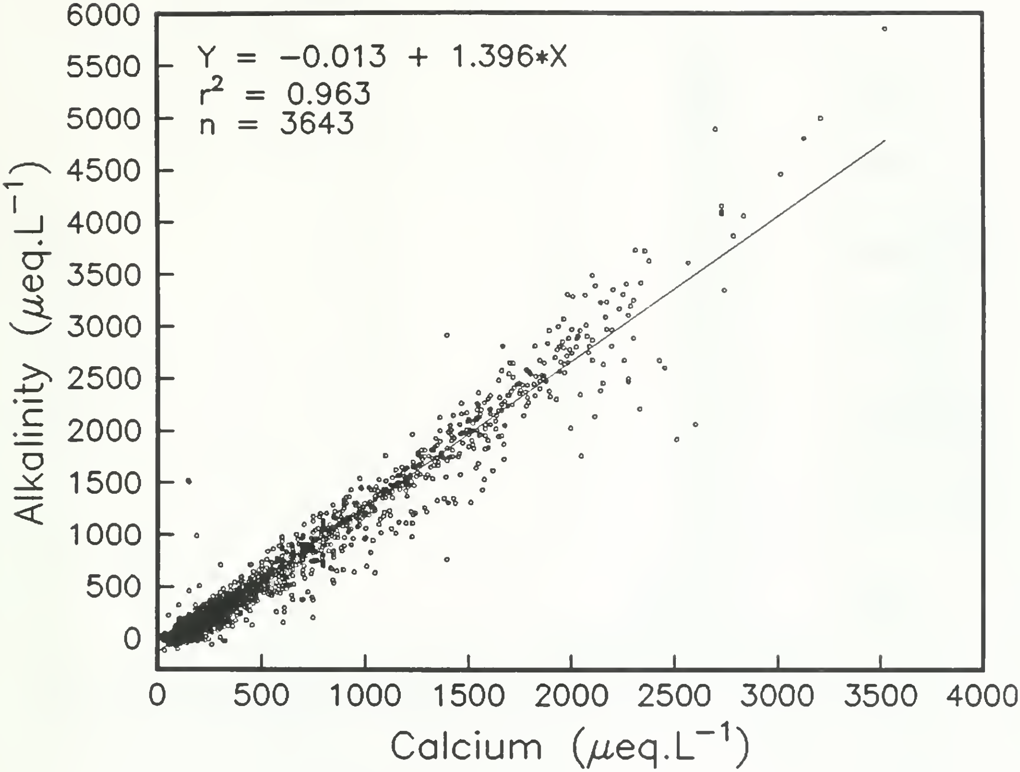

Figure 3.8: The relationship between calcium and alkalinity in Ontario lakes.

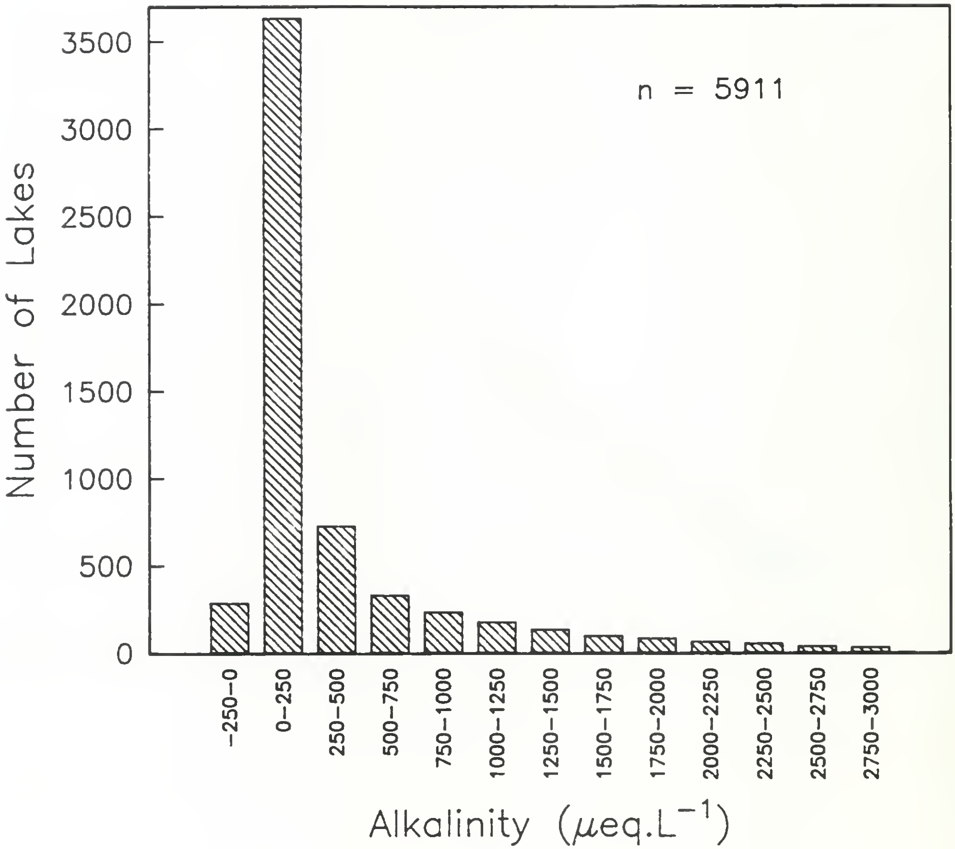

Figure 3.9: Distribution of alkalinity in Ontario lakes.

Table 3.2: Statistical summary for alkalinity and major anions in solution (μeq L^{-1})

	Alkalinity	Sulphate	Chloride	Nitrate
n	5911	3599	996	377
Mean	380	135	27.2	0.86
Minimum	-216	6.5	<0.3	0.02
Maximum	5851	720	2,158	6.86
First Quartile	49	85.3	4.9	0.40
Median	127	137	8.5	0.65
Third Quartile	400	171	17	1.13
Std. Deviation	608	68.8	115	0.77
Skewness	2.75	1.41	12.5	2.96
Kurtosis	9.16	6.86	189	15.33

3.2.2 Sulphate

Sulphate is a relatively minor anionic constituent of lakes in northern Ontario. However, in southern Ontario, and particularly in the vicinity of non-ferrous smelters such as Sudbury, Rouyn-Noranda, or the sintering operations in Wawa, sulphate can be the major anion in solution. On average, sulphate comprises 42.0 % of the anions in lakes in this sample. The geographic distribution of sulphate concentrations will be discussed in Section 6. The distribution of sulphate concentrations is shown in Figure 3.10, except for 9 lakes with sulphate concentrations between 500 and 720 μeq.L^{-1}.

3.2.3 Chloride

Chloride is usually a relatively minor anion in solution. In many of the studies from which these data are compiled, chloride was not measured, however, chloride data are available for 996 lakes. The distribution of chloride concentrations for those lakes where the ion was directly measured is shown in Figure 3.11 except for data from 52 lakes with chloride concentrations over 200 μeq.L^{-1}.

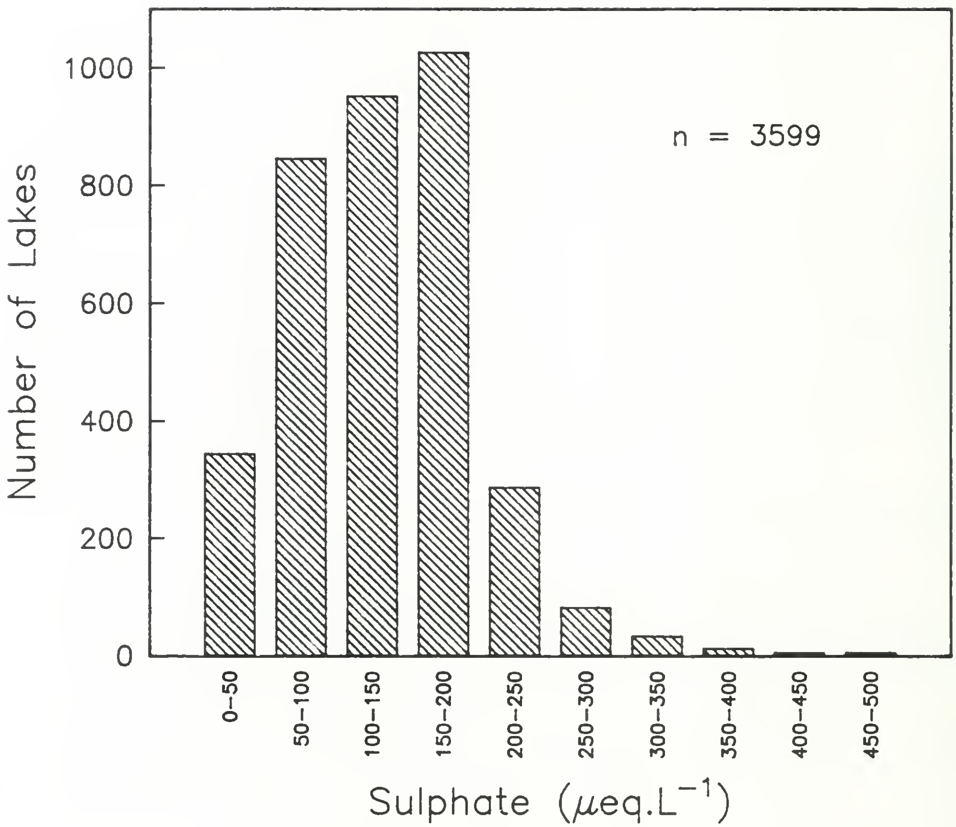

Figure 3.10: Distribution of sulphate in Ontario lakes.

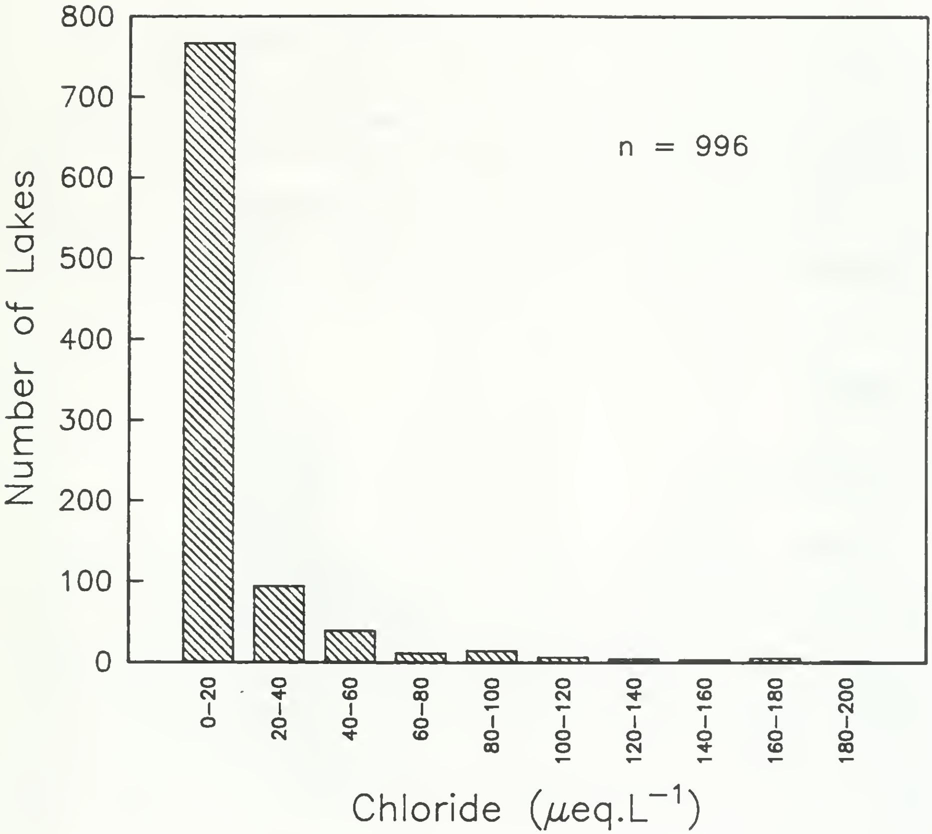

Figure 3.11: Distribution of chloride in Ontario lakes.

3.2.4 Nitrate

Nitrate data are not available for the majority of lakes in the data base. However, there are 377 lakes which have analyses for all of the anions (chloride, sulphate, bicarbonate, organic anions, and nitrate). In this subset, nitrate constitutes an average of 0.28% of the total anions in solution, with a maximum of 2.15%; thus, nitrate is a minor anion in all of the lakes for which nitrate was measured. There is no indication that the nitrate anion plays a significant role in the acid-base status of Ontario lakes at this time. The distribution of nitrate values for those lakes where it was measured is shown in Figure 3.12.

3.3 Metals

3.3.1 Total Aluminum

Aluminum was measured on many of the lakes because of its implication in exacerbating the toxic effects of low pH on biological organisms. As with many of the chemical parameters, total aluminum concentration was strongly skewed to lower values, but ranged as high as 840 $\mu g.L^{-1}$. There was one value of 3200 $\mu g.L^{-1}$ for Lake Abitibi which was not included. This is an extremely large lake on the Ontario-Quebec border, and is the receiving water for a number of rivers which drain the Clay Belt. The lake is frequently turbid with suspended clays, and it was felt that the extraordinarily high aluminum value represented the aluminum content of colloidal clays rather than aluminum dissolved or complexed in solution.

For the purposes of the statistical analysis and other calculations, aluminum values less than the detection limit of 1.0 $\mu g.L^{-1}$ were set to 0.5 $\mu g.L^{-1}$. The distribution of aluminum concentrations in Ontario lakes is shown in Figure 3.13, with the exception of 20 lakes with aluminum concentrations ranging up to 840 $\mu g.L^{-1}$.

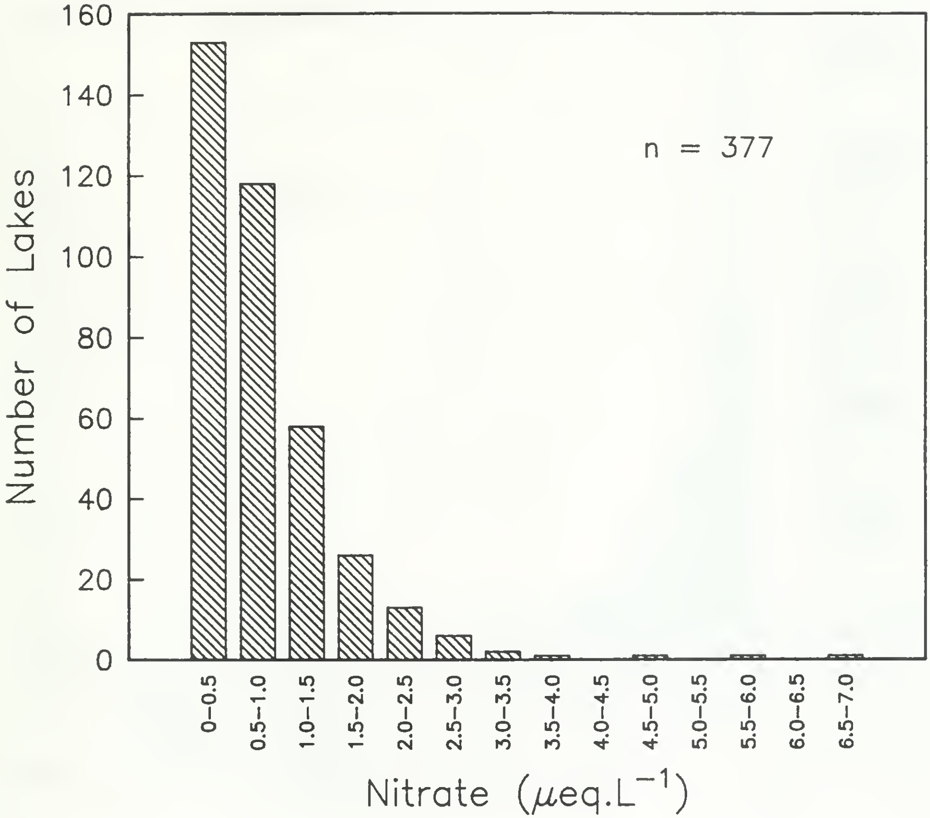

Figure 3.12: Distribution of nitrate in Ontario lakes.

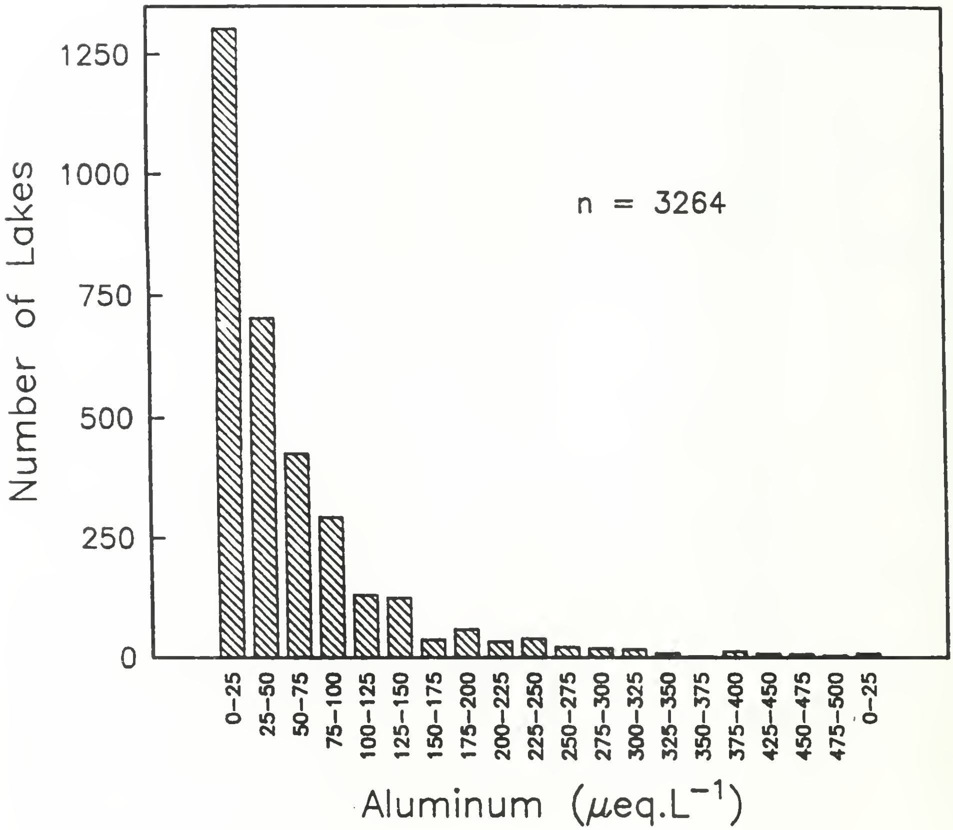

Figure 3.13: Distribution of aluminum in Ontario lakes.

Table 3.3: Statistical summary for aluminum, iron, and manganese ($\mu g\ L^{-1}$)

	Aluminum	Iron	Manganese
n	3264	1267	2952
Mean	63	144	32
Minimum	<1	<5	<1
Maximum	840	1900	580
First Quartile	14	38	8
Median	36	78	21
Third Quartile	77	180	41
Std. Deviation	85	189	39
Skewness	3.448	3.472	4.026
Kurtosis	17.0	18.5	28.4

3.3.2 Iron

There were 1267 lakes sampled for iron. Again, the value for Lake Abitibi (2.98 $mg.L^{-1}$) was excluded on the basis that it probably represented clay suspension rather than dissolved iron. As with the other parameters, values less than the detection limit for the analytical method (5 $\mu g.L^{-1}$) were set to half the detection limit for the purposes of calculating statistics. The distribution of values is shown in Figure 3.14, with the exception of data from 5 lakes with iron values between 1 and 1.9 $mg.L^{-1}$.

3.3.3 Manganese

Manganese data are available for 2952 lakes. The analytical method for manganese had a detection limit of 2 $\mu g.L^{-1}$ so values recorded as 'none detected' were assigned a value of 1 $\mu g.L^{-1}$. Manganese has also been reported as a metal which may potentially be mobilized by acidification. The distribution of values is shown in Figure 3.15.

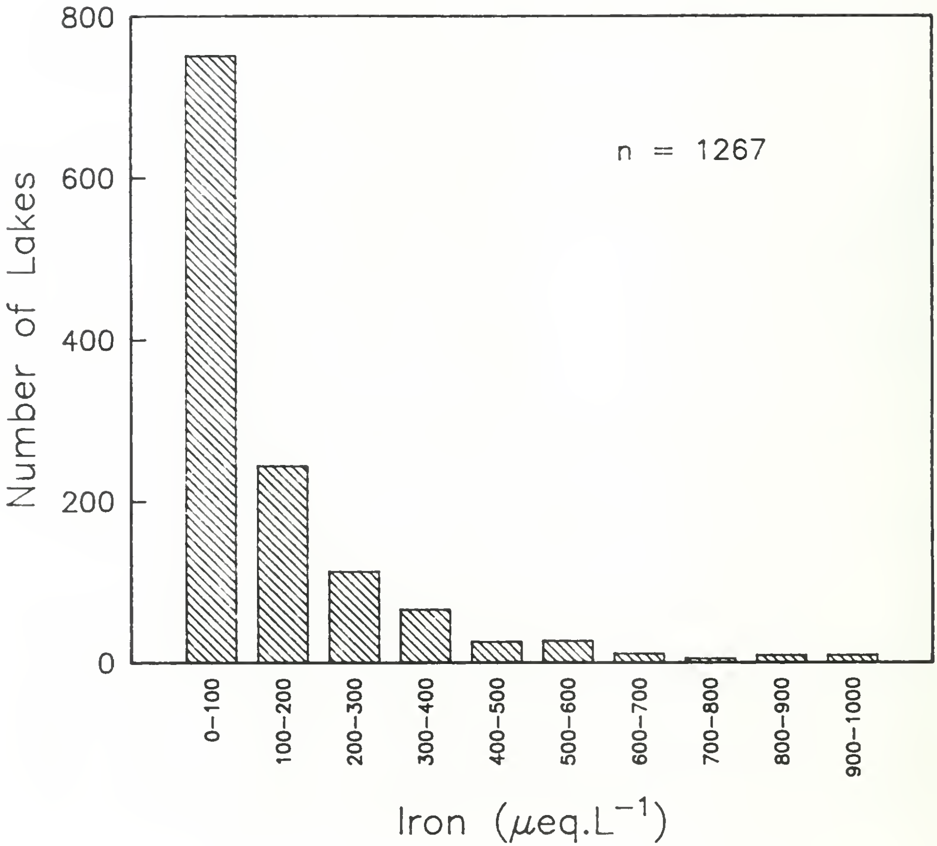

Figure 3.14: Distribution of iron in Ontario lakes.

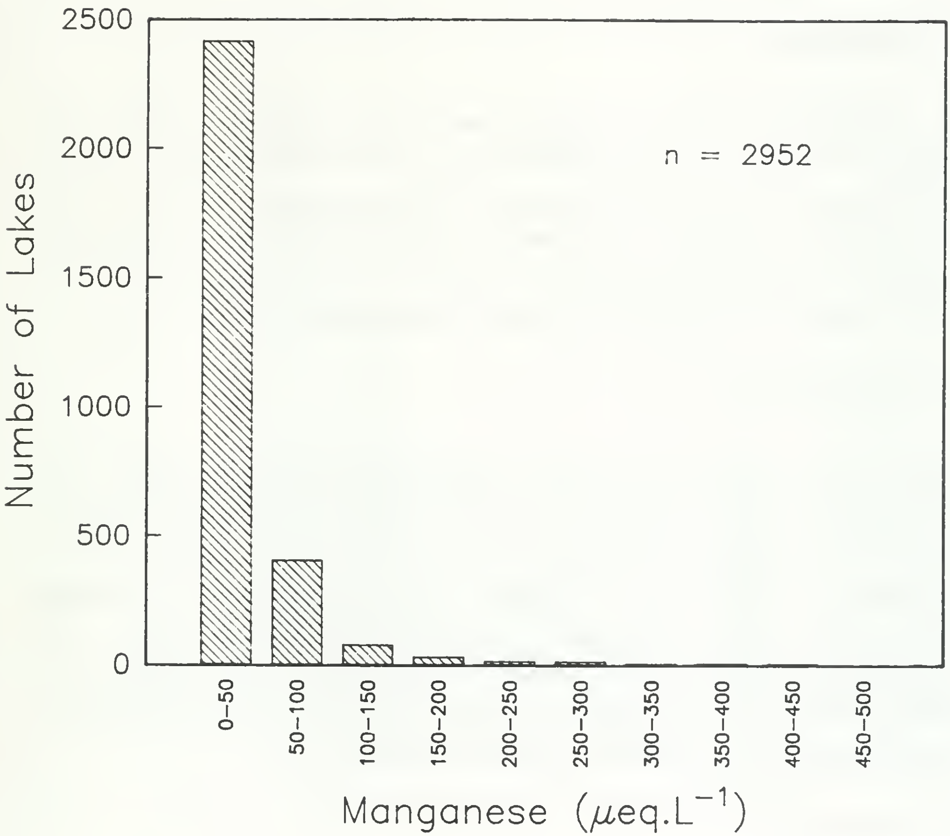

Figure 3.15: Distribution of manganese in Ontario lakes.

3.4 Other Data

3.4.1 Conductivity

The conductivity of a solution is, in part, a measure of the total ionic strength of the solution. As such, it is highly correlated with the total cations or anions in solution ($r^2 > 0.99$ in both cases). The lakes represented in this sample range from very soft (< 10 μS) to very hard (> 1000 μS). The majority of the lakes are softwater, with the median conductivity being 39 μS. The distribution of conductivity values is shown in Figure 3.16, with the exception of 13 lakes with conductivity between 400 and 1320 μS.

3.4.2 Apparent Colour

Apparent colour includes the colour due to dissolved humic and fulvic substances as well as the additional colour contributed by suspended matter since the samples were not filtered prior to measurement in a colorimeter. Analyses for apparent colour were not done after 1983, with the test being abandoned in favour of "true colour" measurements. Negative apparent colours were reported by the laboratory for some extremely clear waters indicating colours less than that of the analytical blank. The distribution of observed values is shown in Figure 3.17. There are data from 6 lakes with apparent colour between 200 and 352 Hazen units not shown on Figure 3.17.

3.4.3 True Colour

True colour is theoretically the same as apparent colour with the exception that samples used for true colour measurement were filtered prior to analysis. However, in some comparison samples, true colour was higher than apparent colour. The results of the intercomparison were such that the two methods of measuring colour are not considered to be comparable. The distribution of true colour values is shown in Figure 3.18, except for data from 14 lakes with true colour values between 200 and 337 Hazen units.

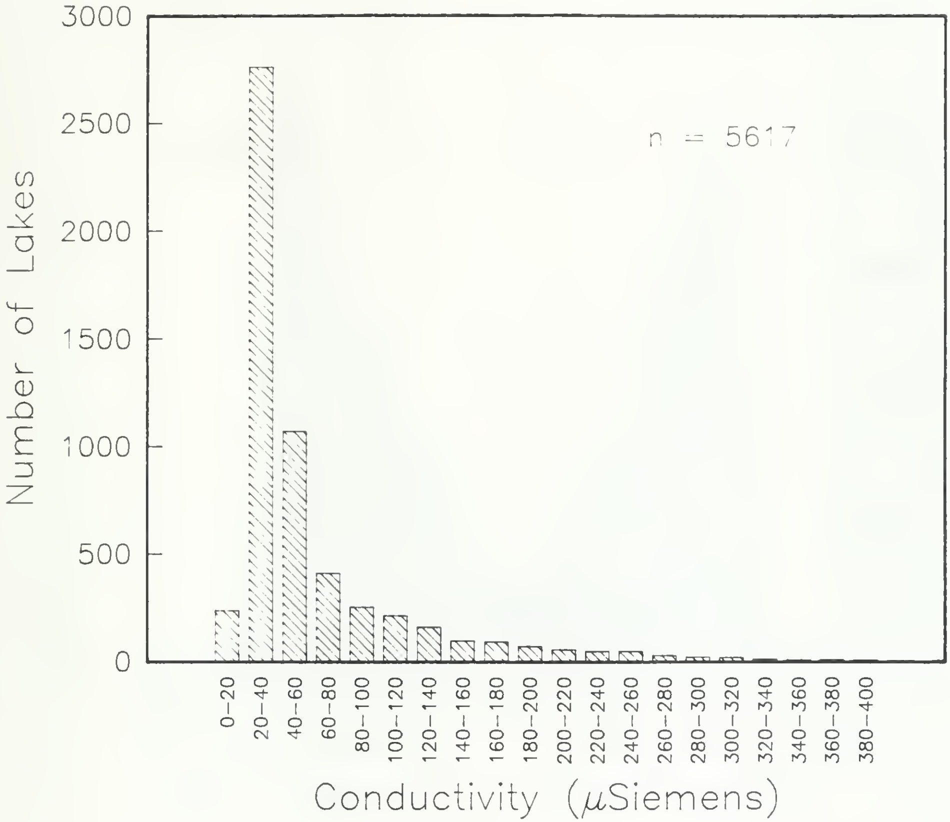

Figure 3.16: Distribution of conductivity in Ontario lakes.

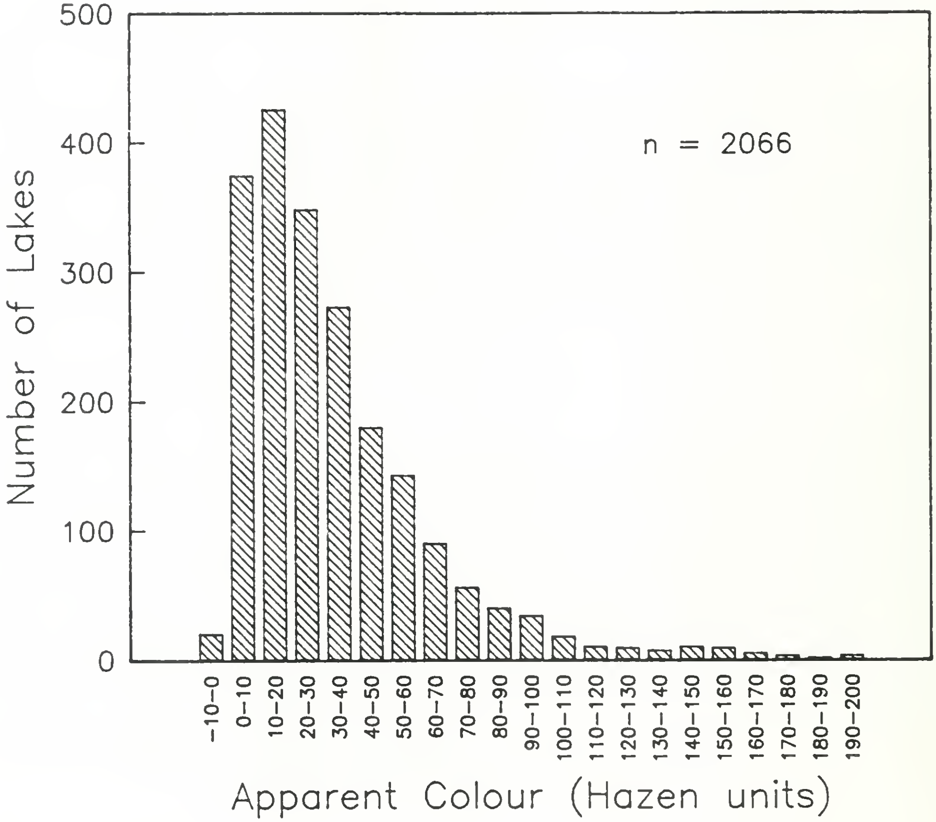

Figure 3.17: Distribution of apparent colour in Ontario lakes.

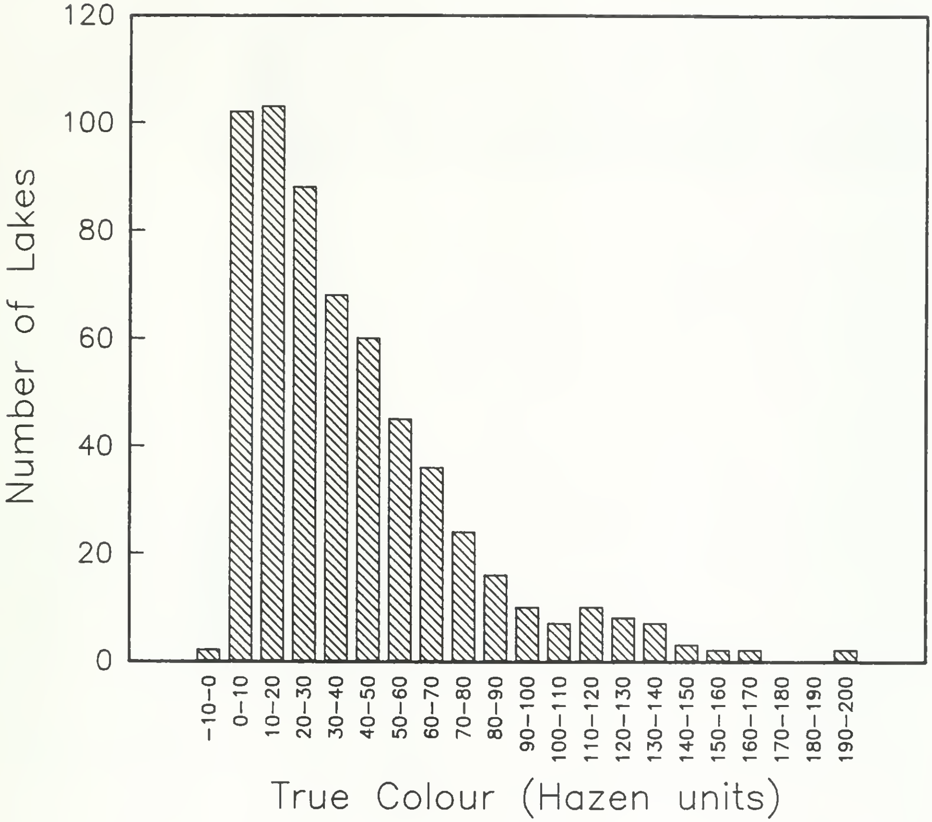

Figure 3.18: Distribution of true colour in Ontario lakes.

3.4.4 Dissolved Organic Carbon

While both colour measurements provide estimates of the amount of fulvic substances in water, dissolved organic carbon (DOC) provides a direct measure of dissolved organic substances. The distribution of dissolved organic carbon values are shown in Figure 3.19, except for data from 6 lakes with DOC values between 31 and 58 $mg.L^{-1}$.

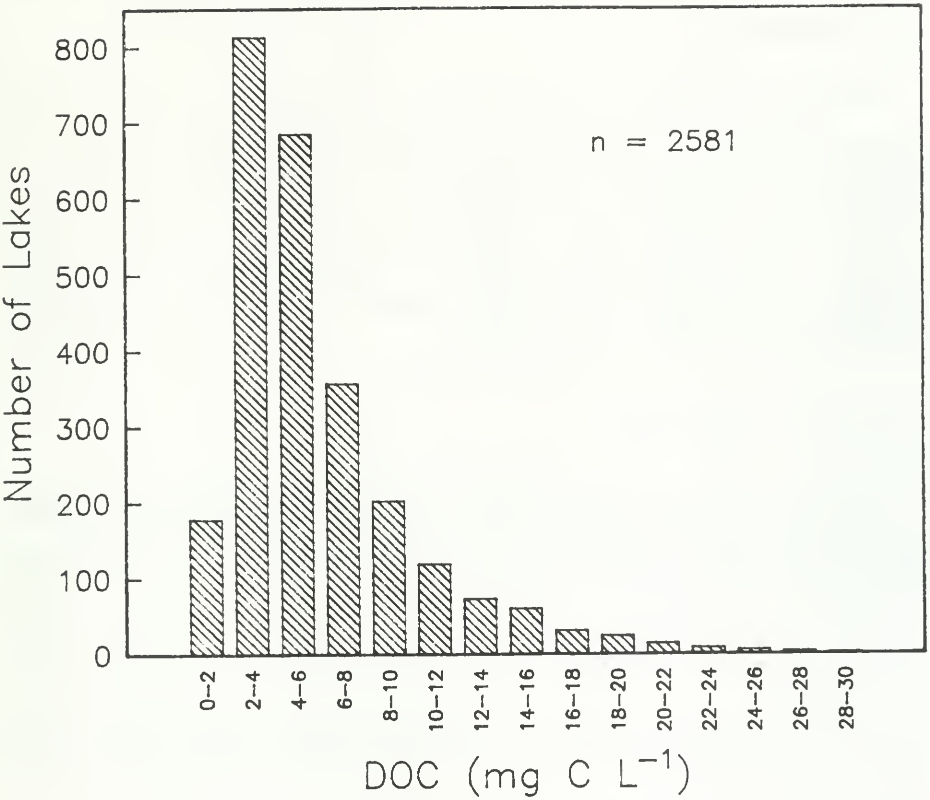

Figure 3.19: Distribution of DOC in Ontario lakes.

4. Calculated Parameters

4.1 Estimated DOC

As discussed in Section 3.4, apparent colour, true colour, and dissolved organic carbon are all estimates of the same thing: the amount of water soluble organic material derived from the decomposition of plant and animal material originating either within a lake or from within its watershed. Since organic anions can be a significant ionic component in coloured, low conductivity lakes, it is important to be able to estimate their abundance. Organic anion concentration can be estimated from dissolved organic carbon and pH (Oliver 1983, Lazerte and Dillon, 1984).

4.1.1 DOC and Apparent Colour

There are 1437 lakes with both apparent colour (COLAP) and dissolved organic carbon measurements. Overall, there is a reasonable correlation between the two variables ($r^2=0.646$). The best fit linear regression is:

$$DOC = 2.254 + 0.0963 * COLAP$$

There is a clear geographic distribution of the residuals, with an overall south-to-north trend to increasing magnitude of the residuals. This trend can be accommodated for by including latitude in the regression equation, or independent equations for each latitude range can be developed. This latter approach appears to yield better predictive equations than a multiple regression (Table 4.1).

Table 4.1: Relationship between DOC and apparent colour. DOC is treated as the dependent variable.

Latitude	n	Intercept	Slope	r^2
4430-4459	61	3.096	0.057	0.575
4500-4559	780	2.486	0.060	0.725
4600-4659	135	2.240	0.083	0.603
4700-4759	145	2.722	0.108	0.715
4800-4859	81	3.920	0.101	0.885
4900-4959	203	3.565	0.136	0.874
5000-5059	32	4.591	0.110	0.888

With the exception of the lakes in the 5000-5059 latitude range, there is steady increase in the slope of the relationship with increasing latitude. Since there are numerous factors which have a south-to-north gradient in Ontario, including such things as mean temperature, amount of rainfall, mean dates for ice cover and ice melt, and sulphur deposition, it is not clear which of the factors is correlated to the change in the DOC-apparent colour slope. For the purposes of estimating dissolved organic carbon when only apparent colour was available, the equation from Table 4.1 appropriate to the location of the lake to be estimated was used.

One problem with the equations in Table 4.1 is the relatively large intercepts (DOC of 2.2 to 4.6 $mg.L^{-1}$). This causes overestimates of DOC for low colour, low conductivity lakes.

4.1.2 Dissolved Organic Carbon and True Colour

There are 466 lakes with both DOC and true colour measurements. The regression between DOC and true colour is given by the equation:

$$DOC = 3.785 + 0.104 * COLTRU$$

with an r^2 of 0.725. In contrast to the DOC-apparent colour relationship, there does not appear to be a compelling reason to look use different equations to estimate DOC from true colour depending on the area. Table 4.2 presents the regression of DOC on true colour for lakes in different latitude categories.

Table 4.2: Relationship between DOC and true colour. DOC is treated as the dependent variable.

Latitude	n	Intercept	Slope	r^2
4430-4459	6	2.126	0.114	0.619
4500-4559	68	3.834	0.075	0.470
4600-4659	53	1.732	0.086	0.776
4700-4759	78	2.374	0.091	0.870
4800-4859	82	2.975	0.116	0.801
4900-4959	46	4.849	0.085	0.784
5000-5059	52	8.281	0.080	0.745
5100-5159	28	9.976	0.047	0.398
5200-5259	53	8.762	0.084	0.553

When estimating DOC when only a true colour measurement was available, the regression equation for all lakes combined was used. The problem with overestimating DOC in low conductivity lakes was not a problem with the true colour measurements, since no lakes with a conductivity < 15 μS had a true colour measurement in the absence of a DOC measurement.

4.2 Organic Anions

Organic anions can be important constituents in Ontario lakes, particularly low conductivity, coloured lakes. The modification of Oliver's method (Oliver, 1983) reported by Lazerte and Dillon (1984) was used to estimate organic anion concentration from pH and measured dissolved organic carbon or from DOC estimated from true or apparent

colour by using the regression equations discussed in Section 4.1. Combining measured dissolved organic carbon measurements from 2581 lakes, and estimated dissolved organic carbon from colour measurements for a further 759 lakes, the DOC concentration (in mg $C.L^{-1}$) data for lakes in the database is summarized in Table 4.3.

Table 4.3: Statistics for DOC data including measured and estimated (from apparent and true colour) values (mg C L^{-1})

n = 3340					
Minimum	0.1	Mean	6.3	Maximum	58.0
First Quartile	3.6	Median	5.2	Third Quartile	7.7
Std. Dev.	4.2	Skewness	2.5	Kurtosis	13.4

From these measured and estimated DOC values, the Lazerte and Dillon modification of the Oliver equation can be used to estimate the organic anion concentration of these lakes. The distribution of the estimated organic anion concentrations are shown in Figure 4.1 and Table 4.4. There are 8 lakes with organic anion concentrations in excess of 300 $\mu eq.L^{-1}$ which are not shown in Figure 4.1.

Table 4.4: Statistics for estimates of organic anion concentration (μeq L^{-1})

n = 3340					
Minimum	0.0	Mean	51.6	Maximum	605.7
First Quartile	23.8	Median	40.2	Third Quartile	66.3
Std. Dev.	43.3	Skewness	2.59	Kurtosis	14.2

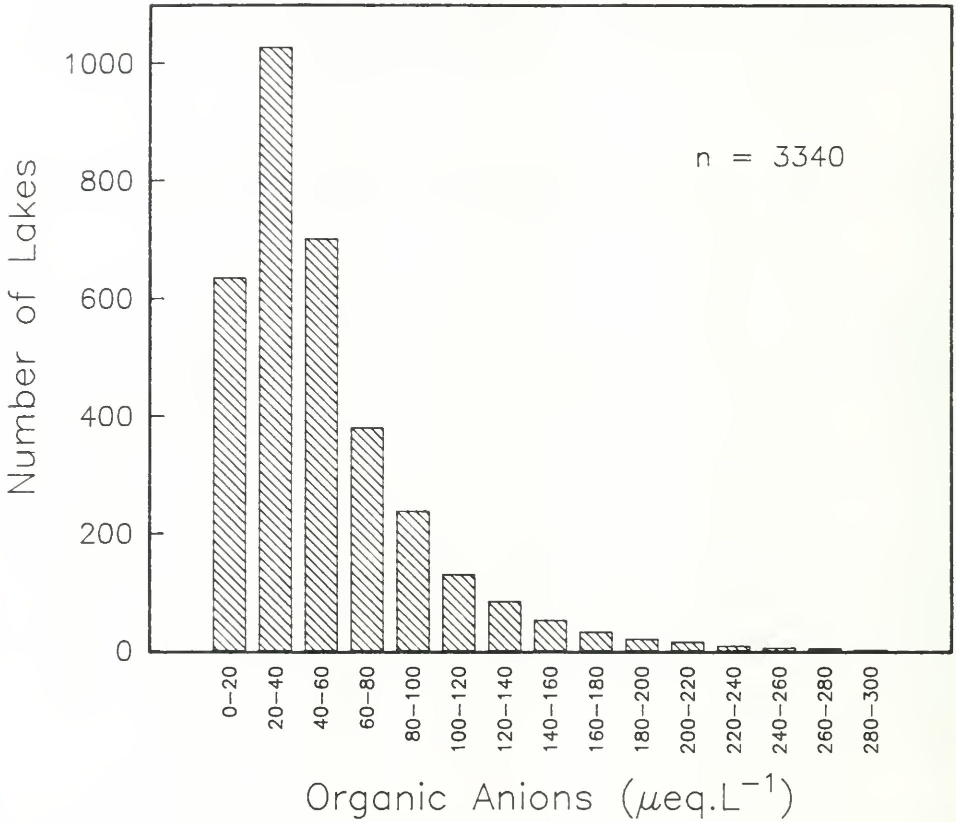

Figure 4.1: Distribution of organic anions in Ontario lakes.

4.3 Estimated Chloride

Chloride in Ontario lakes is a minor anion, with the exception of those lakes receiving runoff from treated roads. Sodium chloride is widely used in Ontario as part of winter road maintenance, and this salt may end up in adjacent water bodies. The result is a strong correlation between sodium and chloride concentrations in Ontario lakes (see Figure 3.5). Sodium values (available for 3304 lakes) were used to estimate chloride levels for those lakes where chloride was not measured. These data, along with the measured chloride concentrations were combined and are presented below as 'estimated chloride'. In several cases, either the estimated or predicted chloride was below the detection limit of the analytical method (0.01 $mg.L^{-1}$ or 0.3 $\mu eq.L^{-1}$). As with other parameters, these data were set to 0.15 $\mu eq.L^{-1}$ (half way between the detection limit and zero) for the purposes of calculating the statistics below, and for ion balancing and other computations.

It should be noted that the good relationship between sodium and chloride is due almost entirely to road salt affected lakes. In the lower concentration ranges (less than 50 $\mu eq.L^{-1}$ Na) the correlation is much poorer (r^2 = 0.07, see Figure 4.2). Also noticeable in Figure 4.2 is considerable stratification in the sodium and chloride values in the outliers of the relationship. Many of these values are from earlier flame photometric sodium analyses and colorimetric chloride analyses. A case may be made that sodium levels above 50 $\mu eq.L^{-1}$ are, at least for softwater lakes, almost certainly associated with road salt. The distribution of measured plus estimated chloride concentrations is shown in Figure 4.3, with the exception of 63 lakes with estimated chloride concentrations between 200 and 2158 $\mu eq.L^{-1}$.

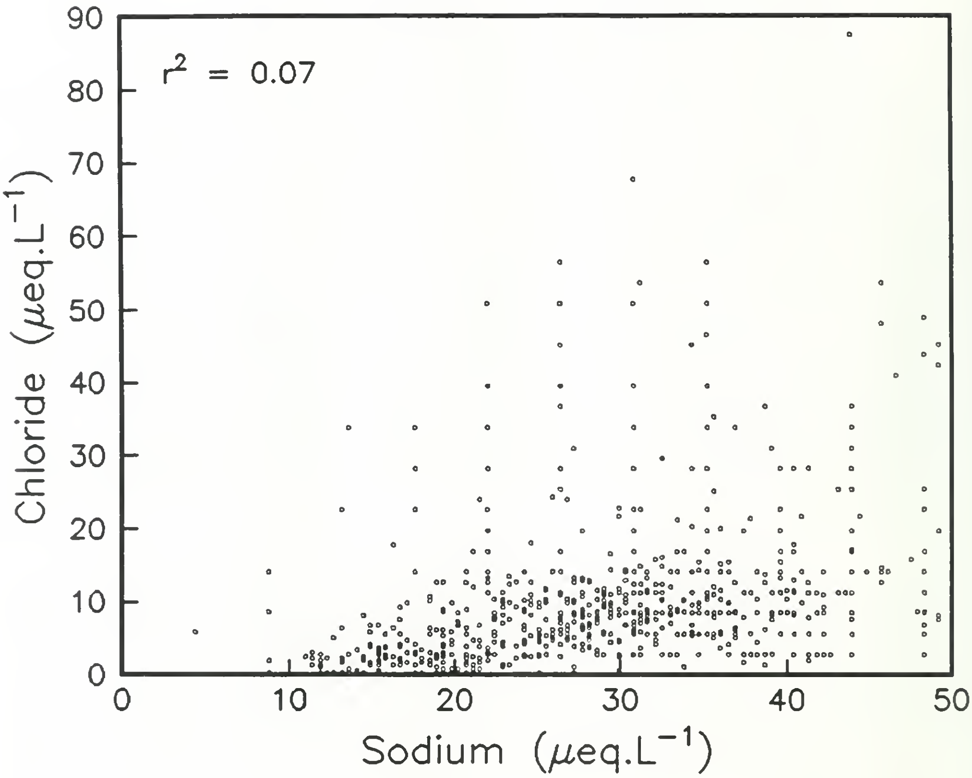

Figure 4.2: The relationship between sodium and chloride in Ontario lakes.

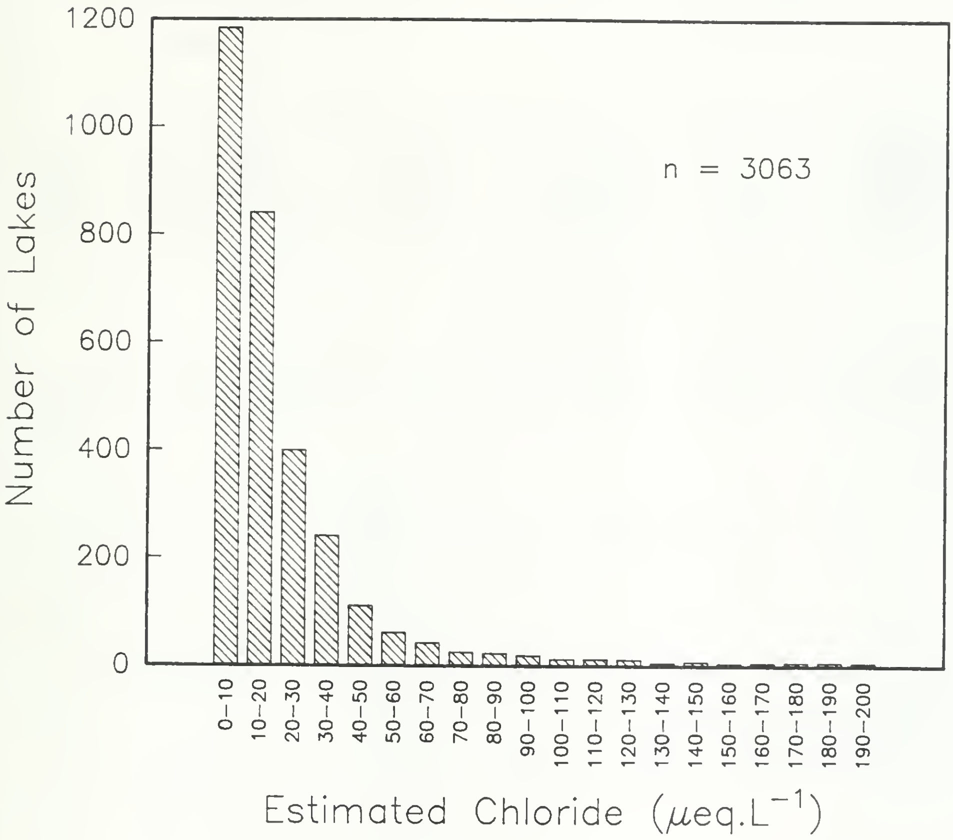

Figure 4.3: Distribution of estimated chloride in Ontario lakes.

Table 4.5: Statistics for Cl data, including measured (n = 996) and estimated (n = 2067) values

n = 3063					
Minimum	0.1	Mean	31.9	Maximum	2157.8
First Quartile	6.8	Median	13.9	Third Quartile	26.1
Std. Dev.	104.0	Skewness	11.9	Kurtosis	174.6

5. Data Validation

5.1 Ion Balancing

One method of assessing the quality of the data is to compare the concentration of all of the cations and anions in equivalence units. These concentrations should, of course, balance, and those lakes whose anions and cations are seriously mismatched have either unmeasured ions in solution, or reflect analytical problems with one or more of the measurements.

The ion balancing procedure used here makes use of estimates for missing data according to methods outlined in Section 4. The specific assumptions, by parameter, were:

Potassium - assumed to be zero if value is missing

Chloride - estimated from sodium if value is missing

Organic Anions - estimated from DOC and pH with the Lazerte and Dillon (1984) equation. For some lakes, DOC was estimated from colour according to methods outlined in Section 4.

$$A^- = (K*C_t)/(K+H^+)$$

where $H^+ = 10^{-pH}$

$$K = 10^{-pK}$$

$$pK = 0.96 + 0.90*pH - 0.039*pH^2$$

and $C_t = 10.9*DOC - 13.7$

Aluminum	- added as a cation assuming oxidation states listed in below. $pH < 5.0$ — 3^+ $5.0 < pH < 5.5$ — 2.5^+ $5.5 < pH < 6.0$ — 2^+ $pH > 6.0$ — 1^+ If aluminum was missing, it was assumed to be zero.
Manganese	- added as a divalent cation, but assumed to be zero if the value was missing
Iron	- added as a divalent cation, but assumed to be zero if the value was missing
Nitrate	- added as an anion, but assumed to be zero if the value was missing
Bicarbonate	- estimated from alkalinity, since DIC was not measured

With these assumptions, the minimum data needed to calculate an ion balance included: pH, alkalinity, colour or DOC, calcium, magnesium, sodium, and sulphate. Out of the 6000 lakes in the data base, there were 2987 with enough data to calculate an ion balance; the results are presented in Table 5.1 and Figure 5.1. The statistics are shown for the percent difference between cations and anions, where the percent difference is $[abs(\Sigma+-\Sigma-)/\{0.5*(\Sigma++\Sigma-)\}]*100$.

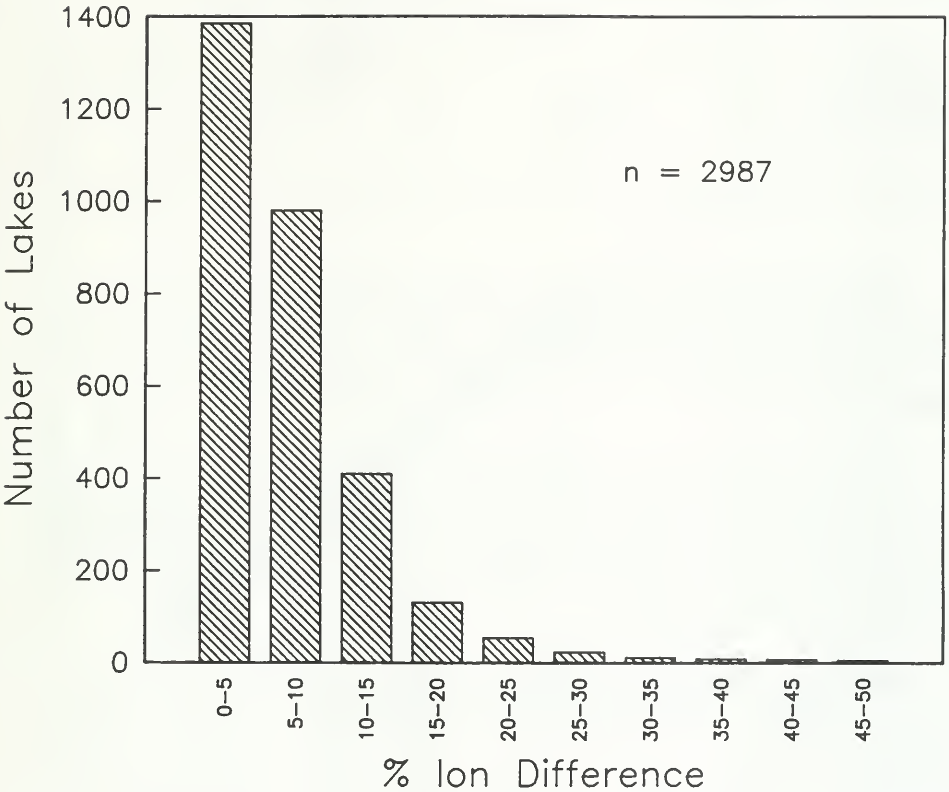

Figure 5.1: Observed percent ion difference for lakes in the database where calculation was possible.

Table 5.1: Summary of % difference between cations and anions

n = 2987					
Minimum	0.0	Mean	7.4	Maximum	123.4
First Quartile	2.7	Median	5.7	Third Quartile	9.7

The ion balance results are very encouraging considering the diverse data sources and the assumptions made in attempting the ion balance. Of the 2987 lakes with enough data to attempt an ion balance, 2291 or 77 % agreed to within 10 %, and 2843 or 95 % agreed to within 20 %.

One problem with using 'percentage difference' as a criterion for comparison arises with very dilute lakes. In lakes with low ionic strength, (conductivity < 15 μS), small analytical errors can result in large ionic imbalances. For 16 of these dilute lakes, the mean percent difference was 17%.

Observations regarding data quality can be derived from the results of the ion balancing. Analyses prior to 1982 from the Northwest region were done in the MOE Thunder Bay laboratory. The colorimetric method for calcium and magnesium reported these cations to the nearest 1 $mg.L^{-1}$. The magnesium results, in particular, appear to be high for several lakes. This is evidenced by the fact that of 37 lakes with a ratio of cations to anions greater than 1.3, 33 were from the Northwest and analyzed in the Thunder Bay laboratory prior to 1982.

5.2 Calculated Conductivity

Another less stringent data 'filter' permits a check based on conductivity data. Using the concentrations of major ions, the theoretical conductivity of the lake can be calculated (Amer. Soc. Test. Mat. 1974). The overall relationship between observed and calculated conductivity is very good ($r^2 > 0.99$, Fig 5.2).

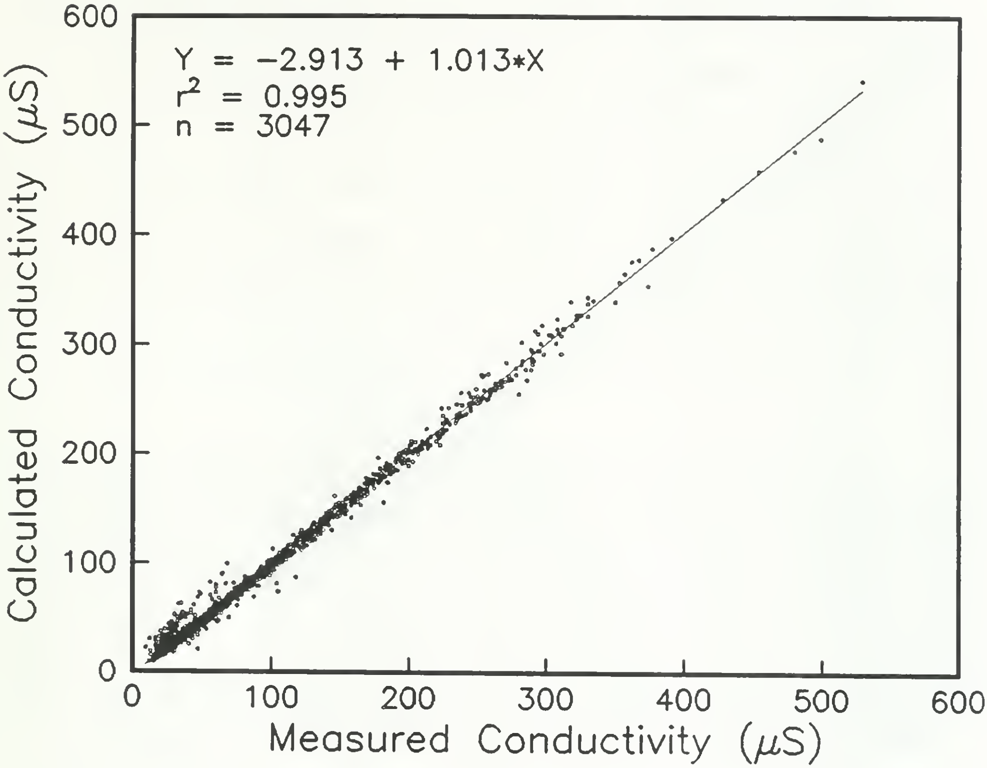

Figure 5.2: Measured vs calculated conductivity for all lakes.

This approach reveals a problem with one of the surveys. Lakes in the DFO National Inventory survey of 1980 have calculated conductivities that are consistently greater than the measured conductivities (Figure 5.3). In addition, ion balancing on the same data shows that the cations were overestimated (mean $\Sigma+/\Sigma-$ of 1.06), even with the absence of potassium data. Presumably, if potassium data were present, both the ion balancing and the conductivity checks would be even worse. The problems associated with that survey are almost certainly, in part, associated with the colourimetric (methylthymol blue) method for sulphate. Problems with the data quality of this survey have been identified earlier (Kelso *et al.* 1986).

5.3 Other Data Relationships

The ion balance and conductivity checks are satisfactory data filters for those lakes with sufficient data to estimate ions. However, there are 3013 lakes with insufficient data to attempt an ion balance or estimate conductivity. For the purposes of making reliable lake population estimates for individual parameters, the pH - alkalinity relationship was examined, with outliers from the relationship flagged as data of dubious quality. Because the pH was frequently a field pH, and because the degree of CO_2 saturation was not controlled, considerable spread in the pH-alkalinity relationship was expected. The pH-alkalinity relationship for lakes with alkalinity values between -100 and 200 $\mu eq.L^{-1}$ is shown in Fig. 5.4. There were 138 lakes where the pH-alkalinity data were sufficiently incongruous so as to exclude the data from further analysis. Lakes which were excluded from subsequent analysis because of gross inconsistencies between pH and alkalinity, because of disagreement between calculated and measured conductivity, or because of ion imbalance are identified.

5.4 Data Quality Code

Based on the completeness of the data and the degree that the data complied with the various validation procedures described above, a data quality code was assigned to each lake. The codes are:

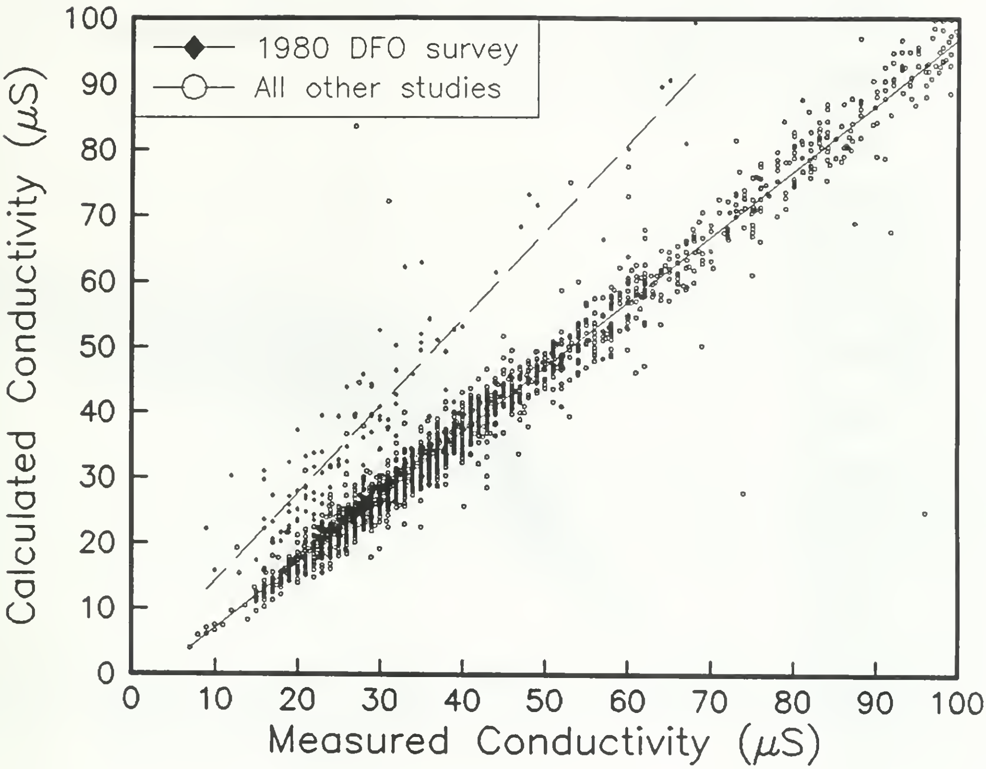

Figure 5.3: Measured vs. calculated conductivity for lakes below 100 μS.

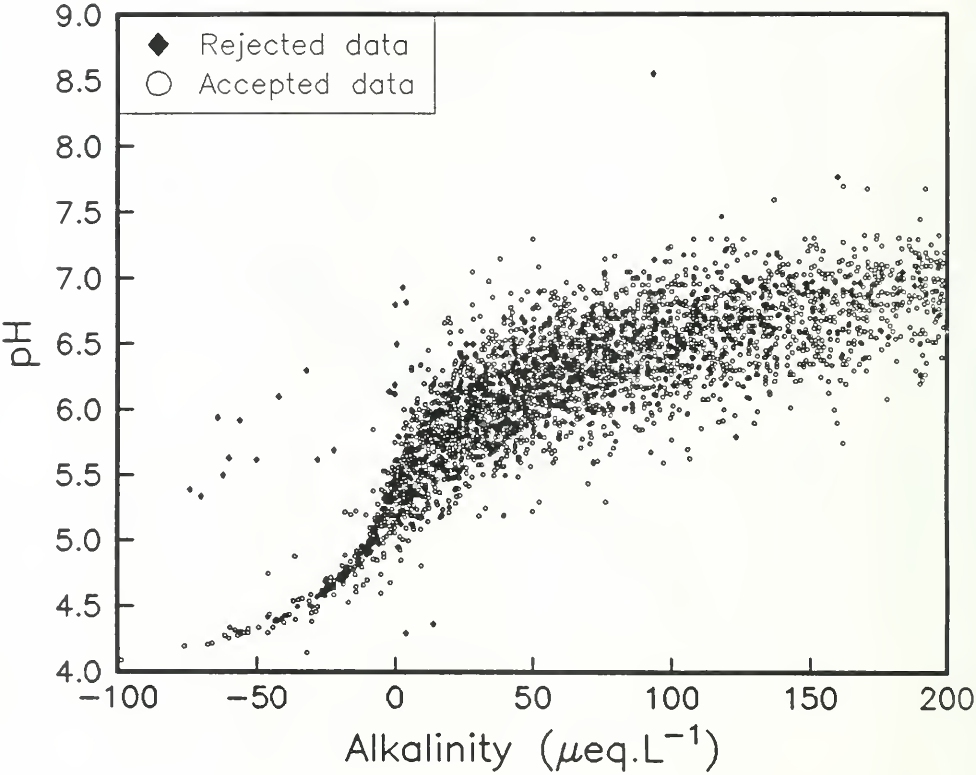

Figure 5.4: pH and alkalinity for lakes < 200 μeq.L^{-1}. Rejected lakes were based on charge balance, theoretical vs measured conductivity or by this relationship.

1 - All major cations and anions were analyzed and there was less than 10% difference between the ions. There are 639 lakes in this category. The lack of chloride data for many of the lakes is a common reason for otherwise good data being placed in another category.

2 - There is agreement to within 10% between the cations and anions. However, one or more of the ionic consituents has been estimated. The most common estimates were chloride (estimated from sodium), organic anions (estimated from colour), or a minor ionic constituent (for example, potassium = 0 if the potassium datum was missing). The specific assumptions for ion balancing are listed in Section 6.1. There are 1633 lakes in this category.

3 - There is agreement to within 20% between the cations and anions. Many of the very dilute lakes ended up in this category, since relatively small differences in analytical measurement can yield significant ion imbalances. There are 687 lakes in this category.

4 - No ion balancing possible due to missing data. However, other data checks indicate that at least the pH and alkalinity data are reasonable. There are 2802 lakes in this category.

5 - Poor data quality is suspected. Either the charge balance deviates by greater than 20%, or the theoretical conductivity differs significantly from the estimated conductivity, or there is a pH-alkalinity inconsistency. There are 143 lakes in this category.

6 - Ion balancing agrees to within 20%, but there is a discrepancy between observed and calculated conductivity. Given ion concentrations, the field conductivity is suspected to be wrong, and the calculated conductivity will be used for lake classification. There are 120 lakes in this category, mostly from the 1980 DFO inventory survey.

6. Sulphur Deposition Zones in Ontario

6.1 Sources of Sulphur Deposition

Lakes in Ontario have been acidified both by local sources of sulphur emissions and by the long range transport of sulphur compounds. Sulphur dioxide emissions from the smelter complex in Sudbury have long been recognized as the cause of local lake acidification (Gorham and Gordon 1960, Beamish and Harvey 1972). Excluding the Sudbury area, lake acidification attributable to longer range transport of sulphur has also been documented (Neary and Dillon 1988).

There have been several attempts to delineate the area in which lake acidification is mostly attributable to the Sudbury emissions rather than long range transport. There are several reasons for this. First, in part of the 'Sudbury zone', biotic effects associated with lake acidification can be exacerbated by elevated levels of metals, particularly copper and nickel, so observations of aquatic effects on fish or other biota may not be generally applicable to other areas. Secondly, the prediction of lake water chemistry response associated with provincial and regional SO_2 emission reduction plans require a distinction between lakes affected primarily by local sources and lakes affected by long range transport. Finally, the sulphur emissions from the smelters in the Sudbury area have dropped by about 80% from the late 1960's, causing a change in local lake water chemistry (Dillon et al. 1986, Keller *et al.* 1986), so it is difficult to attribute lake chemistry to a specific sulphur deposition rate. Monitoring of sulphur deposition in the Sudbury area began in the mid-1970's, so the deposition rate of sulphur causing the widespread lake acidification in the area is unknown (Dillon 1984, Jeffries 1984).

In 1974-76, an extensive survey of 209 lakes within 250 km of Sudbury was conducted to determine the spatial extent of water quality impacts related to the Sudbury smelters (Conroy *et al.* 1978). That study, and subsequent surveys (Keller *et al.* 1980, and Pitblado *et al.* 1980) attempted to delineate the 'Sudbury Zone' according to various individual or combinations of lake water chemistry parameters. Other authors have excluded large areas in the vicinity of the smelters to isolate effects associated with long range transport from the smelter effects (Beggs *et al.* 1985, Neary and Dillon 1988).

6.2 Sulphur Deposition Data

Wet sulphur deposition data (associated with rain or snow) in 1983 was obtained from the APIOS deposition monitoring network (Tang *et al.* 1986a) and from the federal APN network (Table 6.1). Total sulphur deposition was calculated by adding wet sulphate, dry sulphate, and dry sulphur dioxide data (all converted to sulphur). Several

Table 6.1: Sulphur deposition data (from Tang *et. al.* 1986a) for 1983 from monitoring stations in Ontario

Latitude	Longitude	Station	Wet SO_4 $mg.m^{-2}.yr^{-1}$	Dry SO_4 $mg.m^{-2}.yr^{-1}$	Dry SO_2 $mg.m^{-2}.yr^{-1}$	Total S $g.m^{-2}.yr^{-1}$
41°59′15″	82°55′41″	Colchester	3356	479	1280	1.918
42°14′47″	82°13′30″	Merlin	3669	NA	NA	1.849*
42°40′22″	81°09′55″	Pt. Stanley	4040	425	962	1.969
42°42′11″	82°21′13″	Wilkesport	3941	493	1750	2.353
42°49′36″	81°50′04″	Alvinston	3722	NA	NA	1.893*
44°34′54″	81°05′24″	Shallow Lk.	3260	444	602	1.536
43°48′19″	80°54′12″	Palmerston	2597	351	588	1.277
43°17′28″	81°30′03″	Huron Park	3527	NA	NA	1.734*
43°28′39″	80°35′09″	Waterloo	3156	NA	NA	1.467*
45°13′26″	78°55′52″	Dorset	2374	394	211	1.028
43°31′05″	79°55′54″	Milton	3607	388	838	1.750
44°12′46″	79°12′38″	Uxbridge	2798	300	415	1.240
45°00′54″	78°12′58″	Wilberforce	2651	NA	NA	1.161*
44°17′28″	77°47′33″	Campbellford	3053	375	377	1.331
44°37′31″	79°32′08″	Colwater	2292	NA	NA	0.972*
44°56′41″	75°57′48″	Smith's Falls	1941	223	213	0.828
45°19′00″	74°28′13″	Dalhousie Mills	2632	269	287	1.111
45°36′48″	77°12′03″	Golden Lake	2168	325	119	0.891
45°30′57″	79°55′19″	McKellar	3136	349	219	1.271

(cont'd)

Table 6.1: (Cont'd)

Latitude	Longitude	Station	Wet SO_4 $mg.m^{-2}\cdot yr^{-1}$	Dry SO_4 $mg.m^{-2}.yr^{-1}$	Dry SO_2 $mg.m^{-2}.yr^{-1}$	Total S $g.m^{-2}yr^{-1}$
45°59'26"	81°29'18"	Killarney	2918	410	NA	1.316*
46°16'45"	78°49'19"	Mattawa	2510	314	108	0.995
46°58'22"	80°04'40"	Bear Island	892	NA	NA	0.365*
47°26'33"	82°20'14"	Ramsey	659	NA	NA	0.278*
47°39'04"	80°46'32"	Gowganda	1193	293	201	0.596
49°19'16"	82°08'46"	Moonbeam	1375	206	102	0.578
45°32'21"	78°15'35"	Whitney	2268	NA	NA	0.960*
47°03'15"	84°24'00"	Turkey Lake	NA	NA	NA	1.210**
48°50'33"	88°36'45"	Dorion	1139	98	31	0.427
50°10'38"	86°42'90"	Nakina	565	104	23	0.235
50°38'31"	93°13'13"	Ear Falls	507	94	18	0.209
51°27'41"	90°12'04"	Pickle Lake	543	123	20	0.232
48°21'14"	92°12'32"	Lac La Croix	573	NA	NA	0.244*
48°44'24"	91°12'08"	Quetico Centre	1074	134	NA	0.436*
49°39'22"	93°43'28"	ELA	574	NA	NA	0.352*
45°54'08"	77°17'30"	Chalk River	NA	NA	NA	1.217**
42°36'03"	80°27'09"	Long Point	NA	NA	NA	2.274**

* calculated from wet SO_4 (see text)
** 1979-1982 average, obtained from Barrie and Sirois (1986)

of the stations had no dry sulphur deposition measurements. To provide an estimate of dry sulphur deposition, the dry component (SO_2+SO_4) was regressed on the wet sulphur deposition measurement. There was a good correlation between wet sulphur deposition and dry sulphur deposition for the twenty stations for which both data were available (Figure 6.1). Those stations for which no dry deposition data were available had estimated dry sulphur deposition calculated from the regression formula, and the total

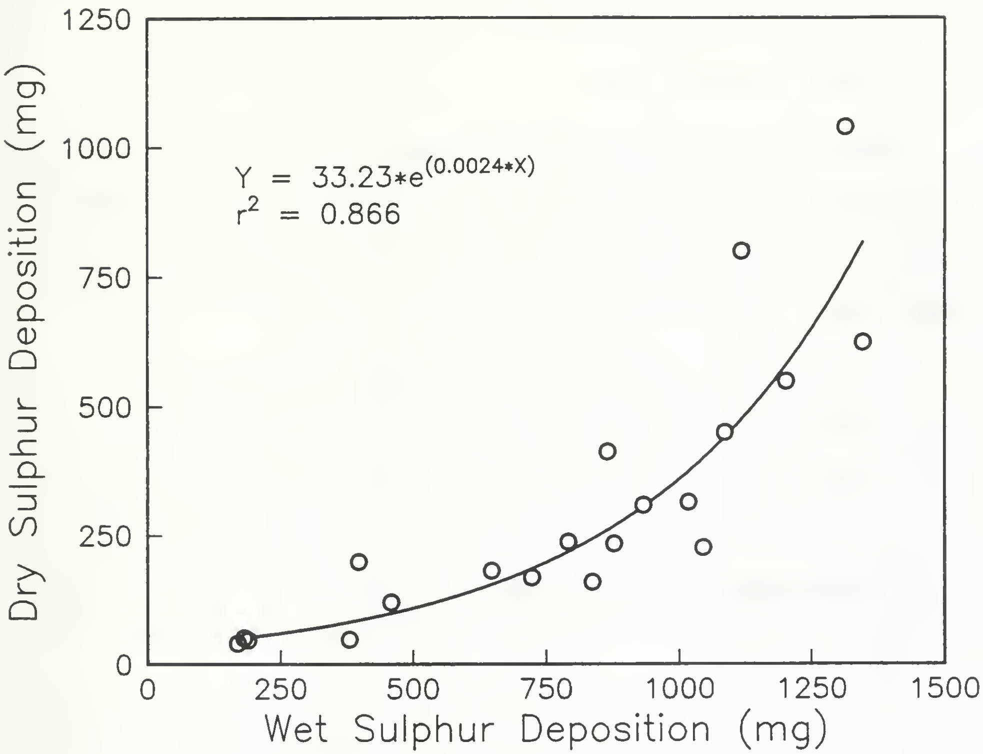

Figure 6.1: Wet vs dry sulphur deposition at 20 stations in Ontario.

sulphur deposition estimate was then made by adding the observed wet sulphur deposition to the estimated dry sulphur deposition.

6.3 Sulphur Deposition Mapping

Mapping was done on a geographic information system called SPANS (SPatial ANalysis System). One of the utilities in this system POTMAP, (or POTential MAPping) permits the construction of areal maps from point data. Sulphur deposition data were imported onto a base map of Ontario obtained from the Environmental Information Systems Division of the Canadian Lands Directorate.

The assumptions behind potential mapping are that the attribute (in this case sulphur deposition) of a given point (the deposition monitoring station) is related to the attribute values of the points around it, and that this effect is lessened with increasing distance between the points. The weighting function used permitted an outer radius of influence of 300 km for each of the deposition monitoring stations. The weighting function was constructed so that the weighting of adjacent points declined exponentially with distance and was less than 0.5 if the point was greater than 50 km (TYDAC, 1988).

The resulting map (Figure 6.2) has assigned the northern portion of the province (outside the 300 km radius associated with the most northerly deposition monitoring stations) an arbitrary deposition of <0.25 $g.S.m^{-2}.yr^{-1}$. This assumption was felt to be valid in light of the declining sulphur deposition gradient from south to north.

6.4 Water Chemistry Mapping

Data from 2236 lakes were selected between 45°00′ to 50°00 latitude and 77°00′ to 86°00′ longitude. All lakes with alkalinity and sulphate data were used. The location of the lakes is shown in Figure 6.3. The water chemistry mapping was done with the POTMAP utility of SPANS, as described above. Each lake's radius of influence was 30 km, with a decay function such that its influence on nearby points was less than 0.5 at a distance greater than 5 km.

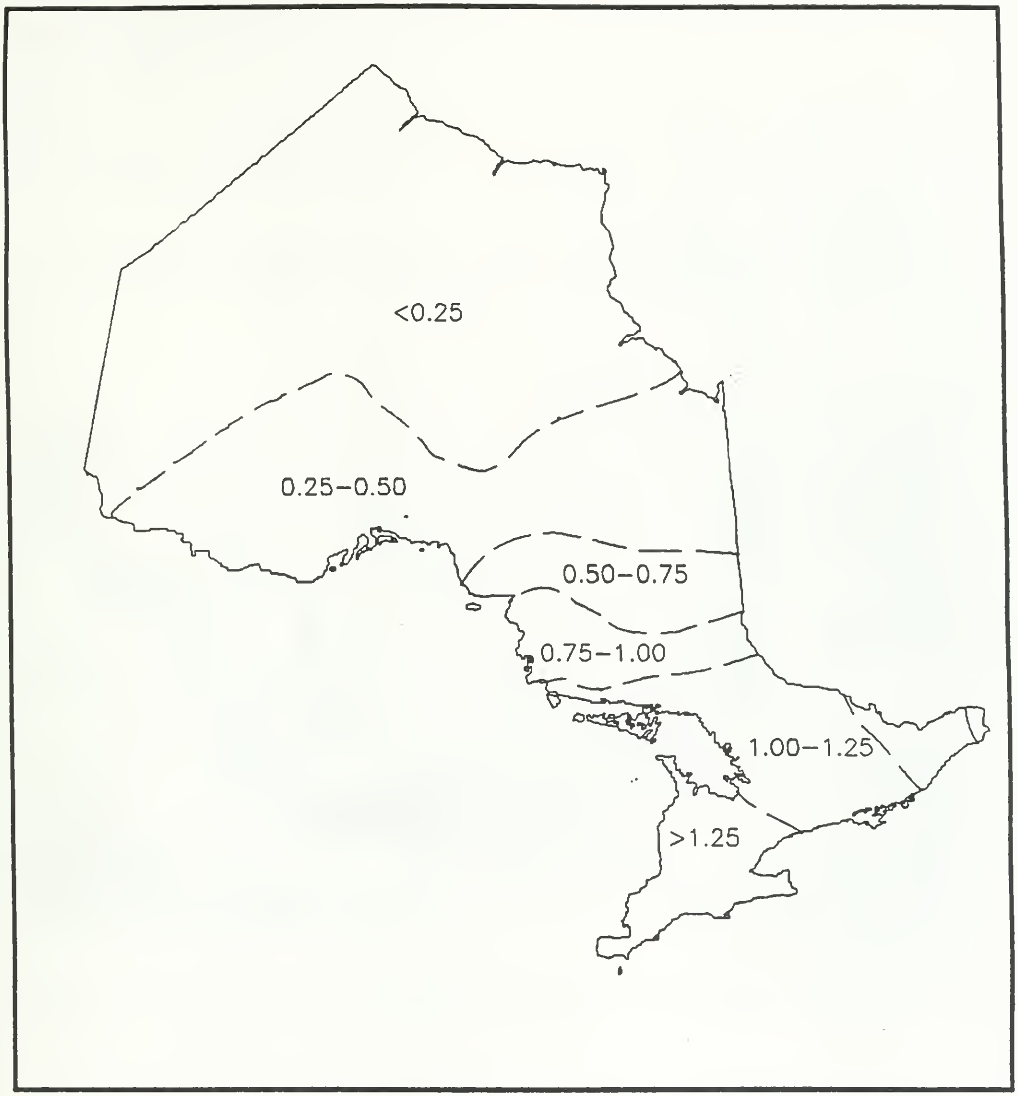

Figure 6.2: Sulphur deposition (g $S.m^{-2}.yr^{-1}$)in 1973.

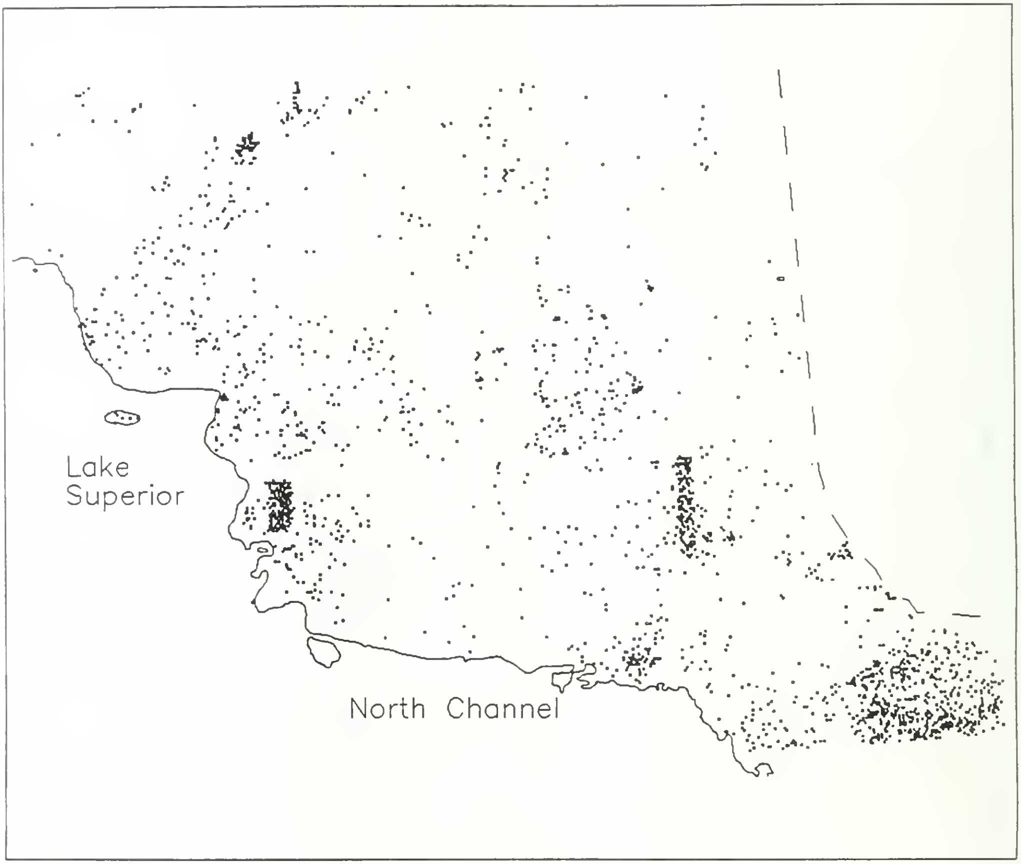

Figure 6.3: Location of lakes with SO_4 and alkalinity data between latitude 45°00-50°00 and longitude 77°00-86°00.

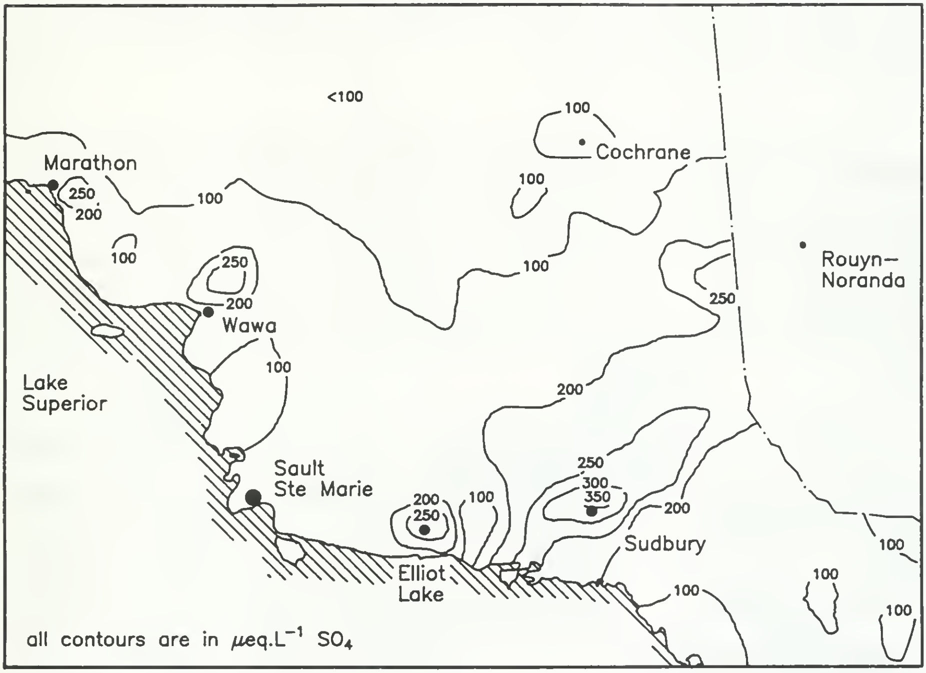

Figure 6.4: Distribution of sulphate concentration ($\mu eq.L^{-1}$) in lakes shown in Figure 6.3.

To determine the 'Sudbury zone', two maps were generated, one of the sulphate concentration of the water, and the other of the ratio of sulphate to (sulphate + alkalinity). Figure 6.4 identifies zones where the concentration of sulphate was higher than that expected considering an overall trend of increasing sulphate in lake water in Ontario from low values in the Northwest to higher values in the South (Neary and Dillon, 1988; also see section 8, below).

The parameter $[SO_4]/([SO_4]+[Alk])$ was used as an estimate of degree of lake acidification. As described in section 4, these are the two major anions in solution in Ontario lakes, and the ratio $[SO_4]/([SO_4]+[Alk])$ can be used as an estimate of the amount of alkalinity which has been replaced by sulphate resulting from the atmospheric input of sulphur. Where this ratio is close to one, the lakes are acidified, whereas a ratio approaching zero indicates a lake with significant amounts of bicarbonate buffering capacity.

Lakes with the $[SO_4]/([SO_4]+[Alk])$ ratio greater than 0.7 have had most of their alkalinity replaced by sulphate. The zone around Sudbury where this occurred corresponds closely with the area where 'Sudbury effects' had been previously documented (Pitblado *et al.* 1980). There are several other areas where this ratio exceeds 0.7 (Figure 6.5). Since these areas do not correspond with the zone where lake water sulphate has been increased by sulphur deposition from the Sudbury smelters, the acidification in these areas is more likely to be attributable to long range transport of sulphur compounds.

6.5 Defining the Sulphur Deposition Zones

The potential mapping of the 1983 sulphur deposition data shows a clear gradient in total sulphur deposition from low deposition rates in the northern part of the province to higher rates in the south. This has been documented previously for wet sulphate deposition, and since the total sulphur deposition is correlated to wet sulphur deposition, it is not surprising to see this trend for total sulphur deposition. At the resolution of the monitoring stations, the effects from the Sudbury smelters are not evident. This is consistent with both previously published deposition maps, and with modelling studies conducted on the effects of the Sudbury smelters (Tang *et al.* 1986b).

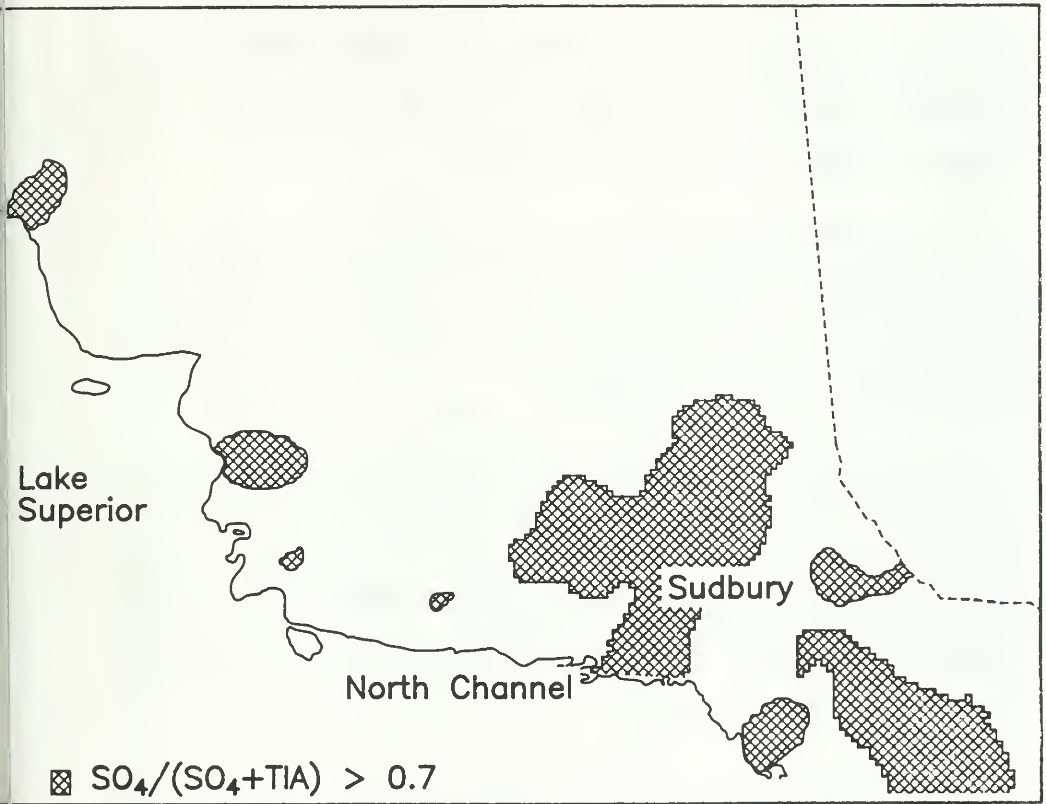

Figure 6.5: Areas where lakes shown in Figure 6.3 have a ratio of SO_4 to (SO_4 + alkalinity) greater than 0.7.

The results of mapping lakewater sulphate (Figure 6.4) showed that there is an area of elevated sulphate extending in a band from the southwest of Sudbury to the northeast, where it connects with an area influenced by the sulphur deposition from the smelters in the Rouyn-Noranda area of Quebec. Small areas with high lakewater sulphate are also evident in the vicinity of the Algoma Steel sintering plant in Wawa, and around the uranium mining and refining activities in Elliot Lake.

The area with $[SO_4]/([SO_4]+[Alk])>0.7$ around Sudbury is somewhat smaller. This is due to the presence of extensive areas of carbonate-rich sedimentary bedrock in parts of the Sudbury basin which extend to the northeast of the region (Cowell 1986). These areas have high lake water sulphate concentrations, but as the buffering capacity of the lakes is high, there has been no significant acidification.

The 'Sudbury zone' was defined as the intersection of the area with lake water sulphate concentration $>200\ \mu eq.L^{-1}$ and the ratio $[SO_4]/([SO_4]+[Alk])>0.7$. The area is shown in Figure 6.6 as 'Zone 7' and covers 17022 km^2. The 'Sudbury zone' extends from the southwest (Killarney) to the north and northeast of Sudbury. There was also a small zone around Elliot Lake which met these criteria, but this area of acidified lakes with high sulphate concentration is due to acid mine drainage rather than the atmospheric input of sulphate (W. Keller, pers. comm.).

For the purposes of stratifying lakes, the 'Sudbury zone' was superimposed on the map of total sulphur deposition (see Figure 6.6). The sulphur deposition associated with each zone is given in Table 6.2.

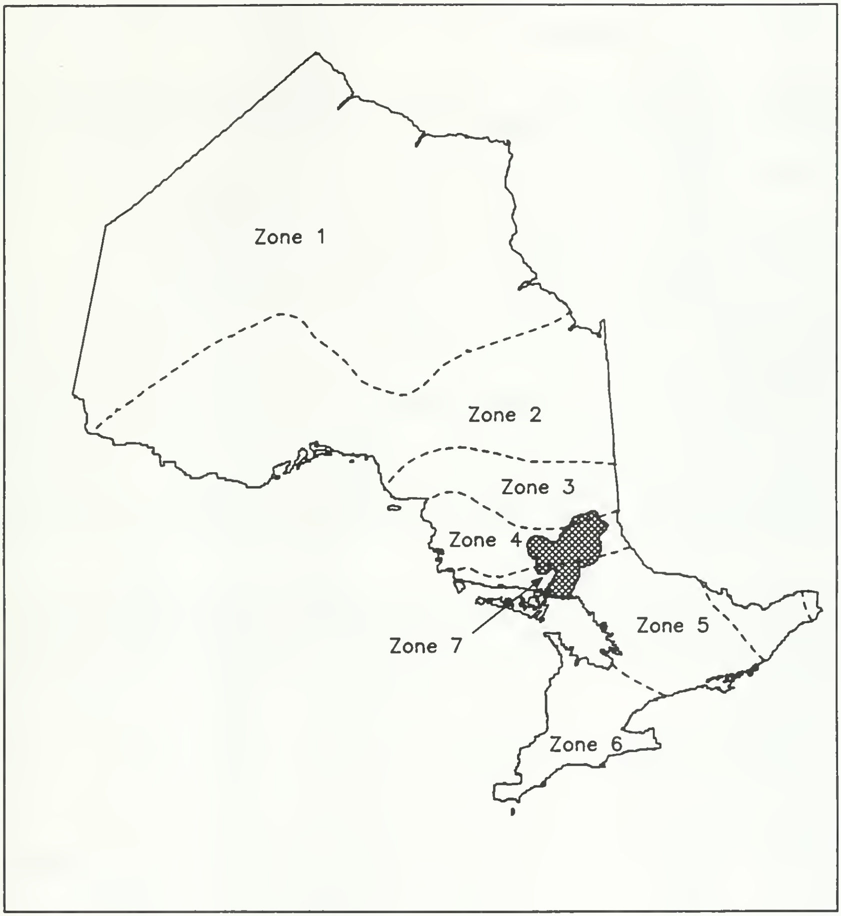

Figure 6.6: Delineation of total sulphur deposition zones in Ontario, including zone 7, believed to be affected by SO_2 point sources at Sudbury.

Table 6.2: Sulphur deposition zones in Ontario

Zone	Sulphur Deposition (g $S.m^{-2}.yr^{-1}$)
1	<0.25
2	0.25-0.50
3	0.50-0.75
4	0.75-1.00
5	1.00-1.25
6	>1.25
7 (Sudbury effects)	unkown, but > 1.25

7. Chemical Characteristics of Lakes by Sulphur Deposition Zone

7.1 Estimate of Lake Numbers and Area by Deposition Zone

Ideally, all of the lakes could be grouped according to deposition zone, and the lake water chemistry extrapolated to the total number of lakes in each zone. However, the only available estimates of total lake populations are organized according to watershed. Therefore, to make lake population estimates for each sulphur deposition zone, it was necessary to fit each quaternary-level watershed into the nearest deposition zone boundary. This was done by assigning each lake to a deposition zone (shown in Figure 7.6) according to it's latitude and longitude using the SPANS 'classify' utility. In most cases, entire watersheds fell into one deposition zone. However, there were several cases where a quaternary watershed was divided between two (or more) deposition zones. In these cases, the watershed was assigned to the deposition zone in which more of the lakes occurred. The exception was Zone 7, the 'Sudbury zone'. If any portion of a quaternary watershed fell into Zone 7, the entire watershed was placed in that zone.

The estimated numbers of lakes in each of the deposition zones are listed in Table 7.1, stratified by lake size range. The details of which watersheds fell into which deposition zones are included in Appendix D.

Table 7.1: Number of lakes in each of four size classes by sulphur deposition zone

S Deposition	Size (ha)				
Zone	>1000	100-999	10-99	1-9.9	Total
1	403	5663	48703	84024	138793
2	296	2507	17992	40605	61400
3	35	383	4155	12862	17435
4	34	253	3423	11725	15435
5	88	704	4353	12672	17817
6	1	33	206	1072	1312
7	37	304	2594	7708	10643
Total	894	9847	81426	170668	262835

A similar breakdown of the area of lakes in each deposition zone, stratified by lake size range, is presented in Table 7.2.

Table 7.2: Total area of lakes in each of four size classes by sulphur deposition zone

S Deposition	Size (ha)				
Zone	>1000	100-999	10-99	1-9.9	Total
1	1816998	1312006	1225330	377725	4732259
2	1623113	621774	504164	155507	2904558
3	100925	94124	109496	38554	343096
4	114505	61790	85074	45735	307104
5	408489	191044	120211	50968	770712
6	1242	9763	5371	3209	19586
7	111254	69445	68424	32389	281513
Total	4176527	2359947	2118269	704085	9358828

7.2 Lake Size Distribution in the Database

There are differences in the distribution of sampled lake sizes in the various zones. Smaller lakes were more heavily sampled in the more southerly deposition zones than in the north. This is partly due to the differences in sampling study design, and partly due to logistical considerations. Many of the northern lakes were sampled from an aircraft, which precludes lakes smaller than 10 ha. Additionally, when helicopters were used to specifically sample lakes in the winter, some of the smaller northern lakes were frozen to the bottom.

The lake size distribution by deposition zone is shown in Figure 7.1 and summarized in Table 7.3.

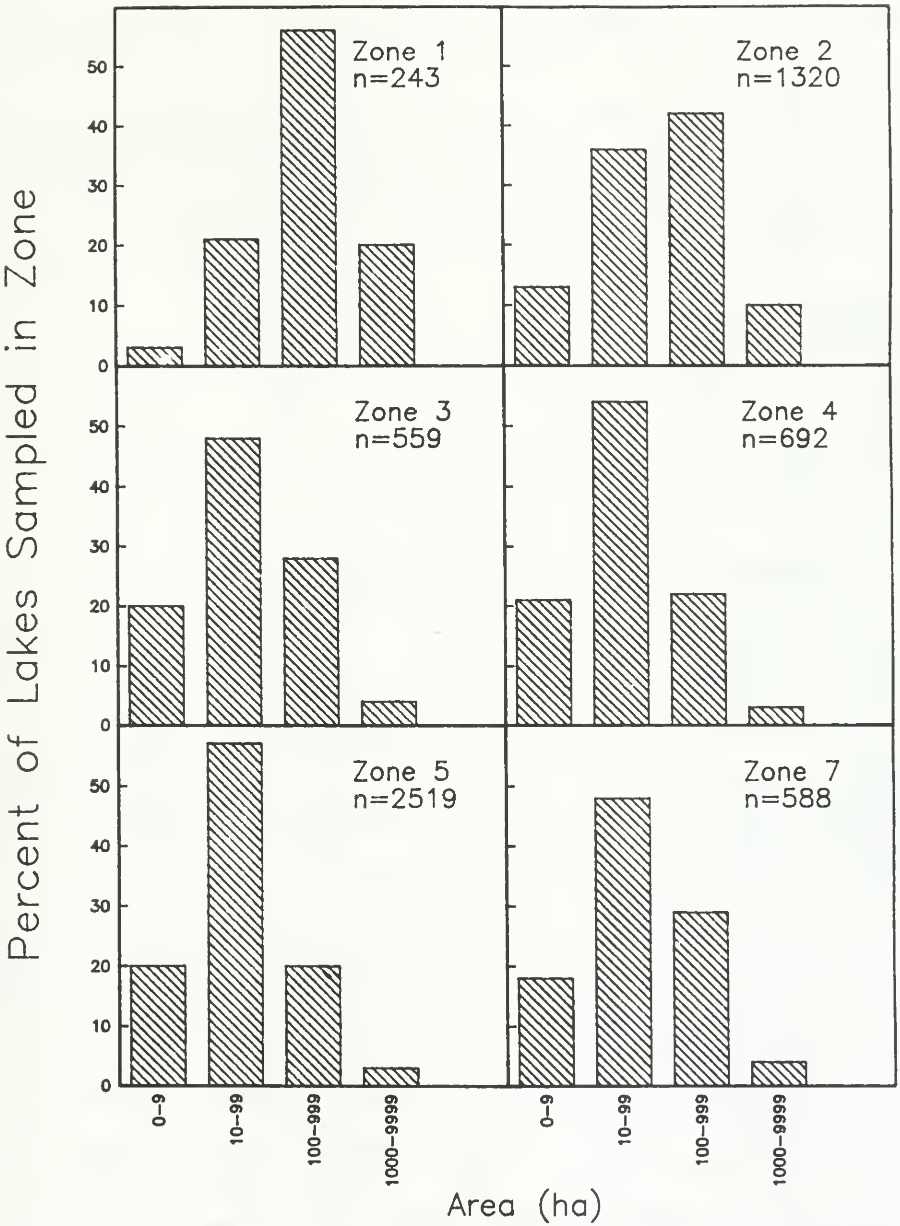

Figure 7.1: Lake area distribution shown as percent of lakes sampled for each sulphur deposition zone.

Table 7.3: Lake size distribution by deposition zone

	S Deposition Zone					
	1	2	3	4	5	7
Lake Size						
Median	319	115	52	40	30	51
Q1	108	33	15	13	12	16
Q3	875	332	136	102	94	148
N	231	1223	520	656	2443	558

7.3 Lake Water Chemistry Stratified by Deposition Zone

7.3.1 Data Exclusions

The data description in Section 4 included lakes which were influenced by point sources, and data which could not be validated. For the data analysis below, all data with data quality codes 5 and 6 were excluded. As described earlier the 'Sudbury' zone was treated seperately. In addition, data from lakes close to point sources of either airborne sulphur or acid mine drainage were also excluded. These latter lakes were identified by their proximity to either Wawa, Elliot Lake, or Rouyn-Noranda. They included all lakes within the 150 $\mu eq.L^{-1}$ sulphate isopleths around Elliot Lake and in the Rouyn-Noranda area, and all lakes within the 100 $\mu eq.L^{-1}$ isopleth around Wawa (see Figure 6.3). There were a total of 85 'point source' lakes excluded and a further 260 lakes omitted because of questionable data quality. An additional 24 lakes were excluded because their size was greater than 10000 ha. These lakes ranged up to 400,000 ha in size (Lake Nipigon), and were felt to be non-representative of the overall lake population, primarily because their enormous water volume would make their response time to atmospheric inputs much longer than that for smaller lakes.

7.3.2 Cations

The medians and quartiles of pH, Ca, Mg, Na, and K stratified by sulphur deposition zone are presented in Table 7.4. Medians and quartiles are used because of the highly skewed nature of the distribution of all of the parameters except pH (see Section 3). All of the differences in cations between deposition zones are significant ($p<0.001$).

Table 7.4: Summary of pH and base cation statistics stratified by deposition zone

	S Deposition Zone					
	1	2	3	4	5	7
pH						
Median	7.10	7.30	7.40	6.58	6.36	5.98
Q1	6.89	6.78	7.00	6.12	6.02	5.17
Q3	7.39	7.75	7.74	7.03	6.78	6.67
N	231	1213	517	656	2441	556
Ca						
Median	274	409	514	165	149	140
Q1	200	172	302	97	120	105
Q3	499	1103	818	250	182	197
N	175	716	298	322	1552	311
Mg						
Median	99	164	177	49	66	66
Q1	82	82	99	33	51	52
Q3	197	414	268	72	89	87
N	175	716	297	321	1443	311
Na						
Median	44	38	35	26	34	31
Q1	36	29	29	18	28	26
Q3	53	48	44	35	46	40
N	175	690	255	277	1311	285

(cont'd)

Table 7.4: (Cont'd)

	S Deposition Zone					
	1	2	3	4	5	7
K						
Median	15	13	10	7	12	10
Q1	11	10	7	4	10	9
Q3	19	17	14	10	15	13
N	175	702	252	229	1311	285

Histograms of the pH distribution of lakes in each of the deposition zones are shown in Figure 7.2. There is a shift in the distribution of pH to lower pH values in deposition zones 5 and 7 relative to those found in zones 1, 2, and 3. Zone 4 reappears to be transitional.

The calcium statistics show that zone 2 and to a lesser degree, zone 3 have much higher calcium levels than the other zones. This trend to higher calcium levels is also evident in the calcium histograms displayed in Figure 7.3. This is mostly due to the the fact that some of the lakes are located in the Clay Belt, and in areas of sedimentary rock (see Cowell, 1986) within these zones.

The pattern of magnesium concentrations is closely related to that of calcium, a result that is not surprising given the strong correlation between the variables. Zone 2 has the highest magnesium concentration. Zone 1 and 3 also have a significant proportion of lakes with magnesium concentration in excess of 500 $\mu eq.L^{-1}$. The distribution of magnesium concentrations is shown in Figure 7.4.

The distribution of sodium shows less variability between deposition zones (Figure 7.5). Despite a relative lack of hardwater lakes and a lower density of roads, zone 1 has the highest median sodium concentration. This may be due to the relatively

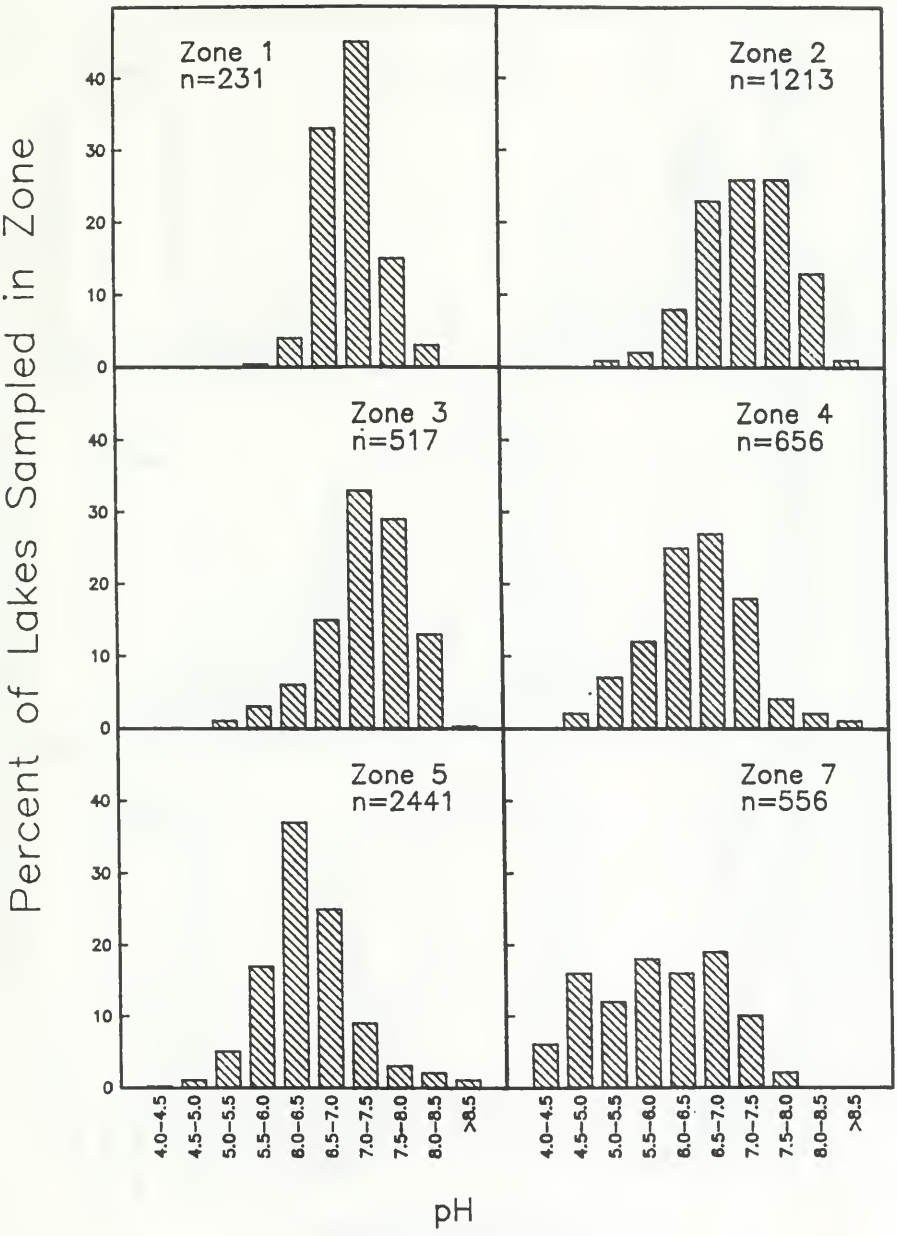

Figure 7.2: pH distribution shown as percent of lakes sampled for each suphur deposition zone.

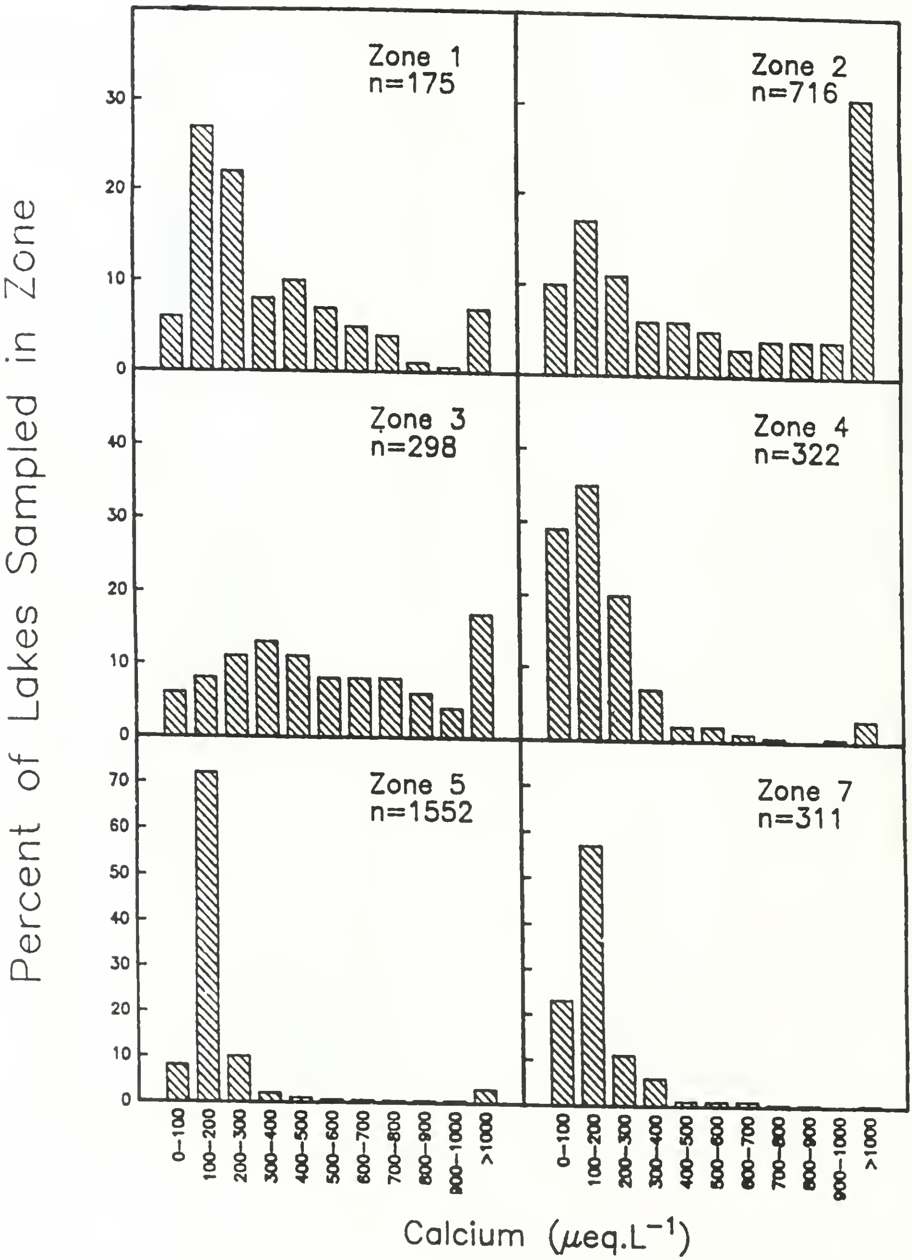

Figure 7.3: Calcium distribution shown as percent of lakes sampled for each sulphur deposition zone.

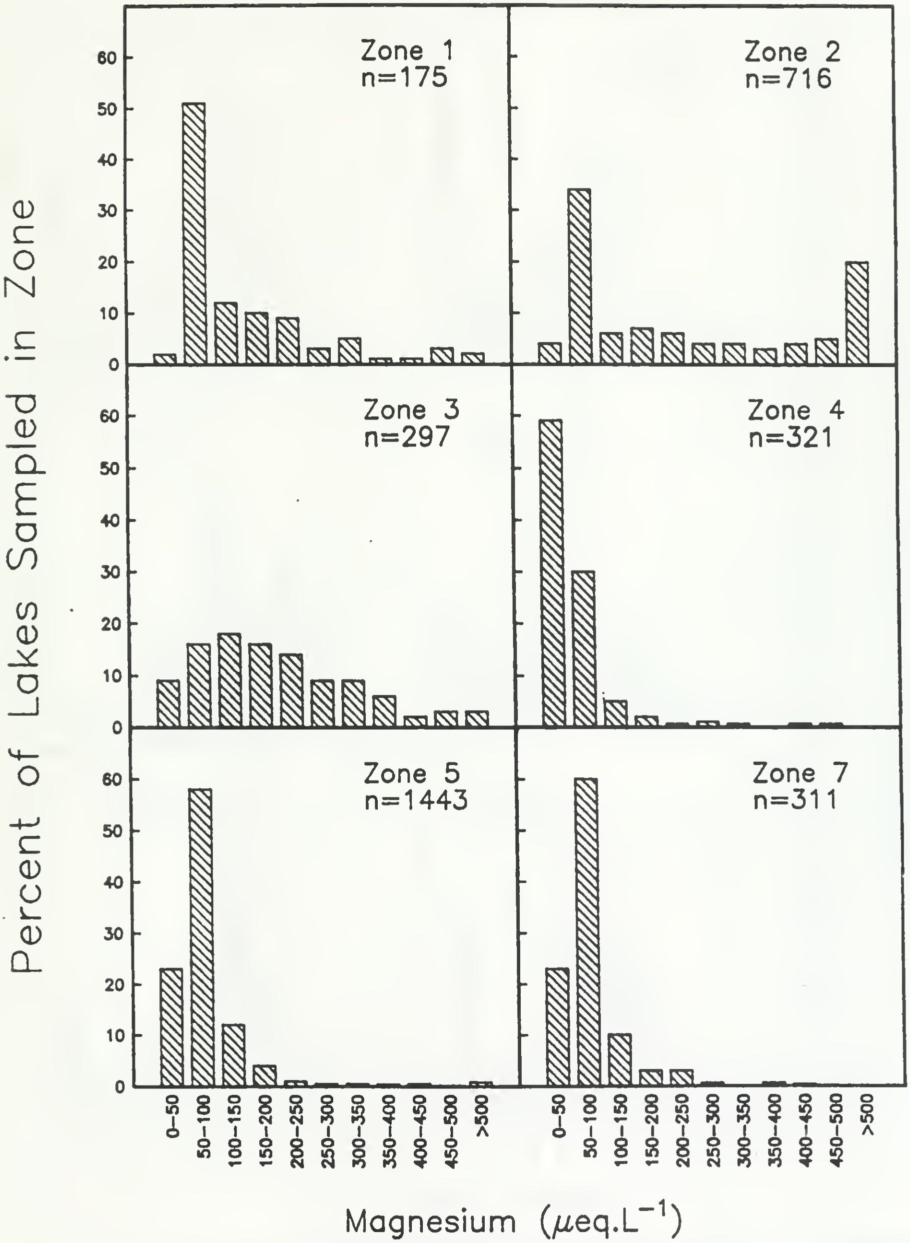

Figure 7.4: Magnesium distribution shown as percent of lakes sampled for each suphur deposition zone.

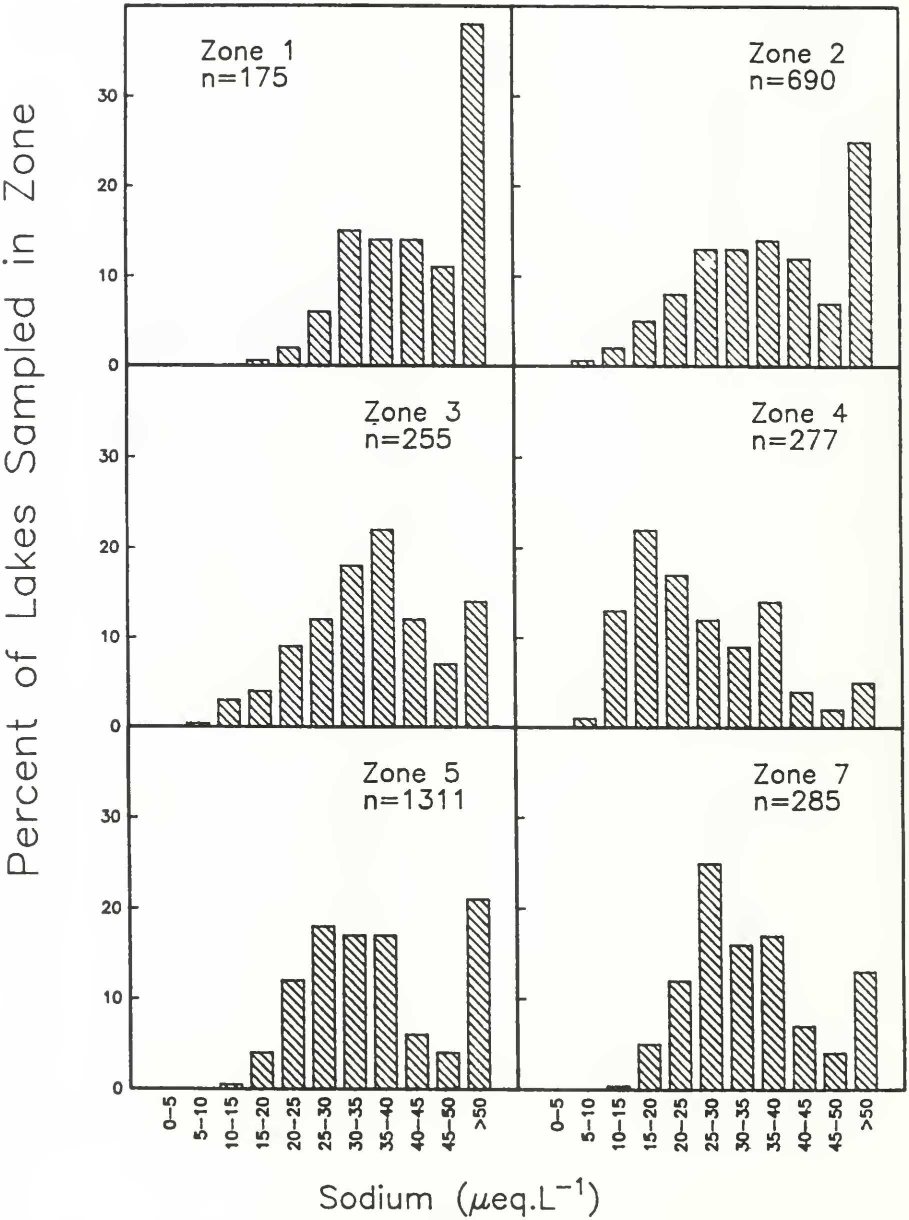

Figure 7.5: Sodium distribution shown as percent of lakes sampled for each suphur deposition zone.

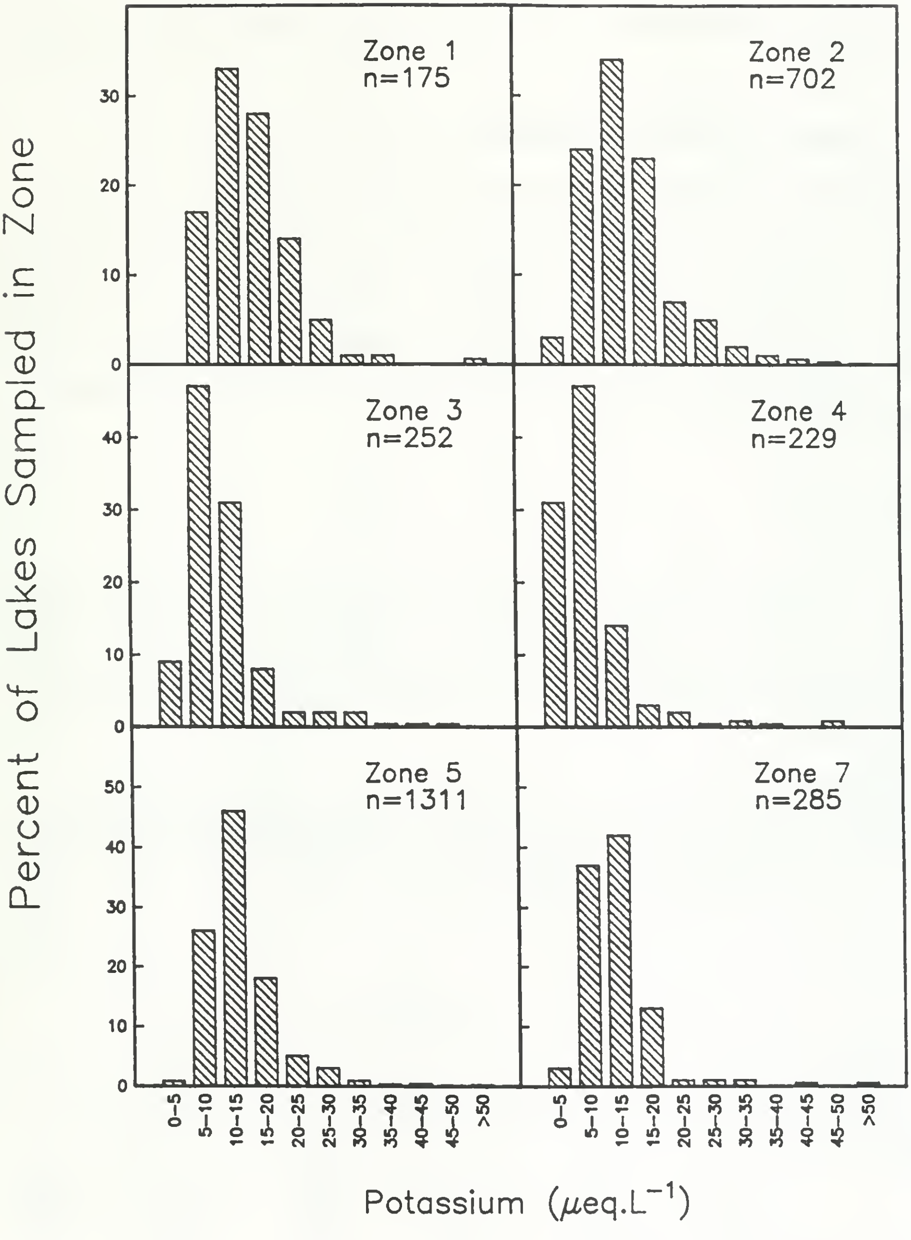

Figure 7.6: Potassium distribution shown as percent of lakes sampled for each suphur deposition zone.

enriched sodium concentrations in the bedrock in areas of northwestern Ontario (Brunskill *et al.* 1971).

Potassium also shows little variability between zones. The median potassium value ranges from 7 to 15 $\mu eq.L^{-1}$, and the third quartiles of the distributions are consistently under 20 $\mu eq.L^{-1}$. The potassium concentration in wet deposition is higher in northwestern Ontario than in most other regions of the province (Tang *et al.* 1986). The source of potassium is probably associated with fertilizer application in the prairie provinces. Some of this material is undoubtedly transported with dust in the prevailing west to east air flows in this area, and may account for the slightly higher potassium concentrations in lakes in this zone.

7.3.3 Anions

The relative anionic composition of lake water shows much more variability from zone to zone. This is apparent from the data presented in Table 7.5. There are strong trends for several of the anions from deposition zone to deposition zone which will be discussed separately. Differences in all anion concentrations between deposition zones are significant ($p<0.001$).

Table 7.5: Summary of anion statistics stratified by deposition zone (alkalinity is treated as an anion since it is assumed to approximate $HCO_3^- + CO_3^{2-}$). A^- is estimated organic anion concentration.

	S Deposition Zone					
	1	2	3	4	5	7
SO_4						
Median	34	69	117	102	157	222
Q1	24	47	98	86	139	198
Q3	65	88	152	131	177	260
N	146	693	297	321	1500	313

(cont'd)

Table 7.5: (Cont'd)

	S Deposition Zone					
	1	2	3	4	5	7
Alk						
Median	335	467	495	94	76	22
Q1	191	171	244	40	39	-4
Q3	672	1205	876	206	149	98
N	231	1210	513	651	2401	545
Cl						
Median	3	8	17	4	11	8
Q1	3	6	17	2	8	5
Q3	8	25	37	8	23	14
N	94	112	15	187	297	136
A-						
Median	89	65	63	44	42	26
Q1	41	41	39	32	32	17
Q3	137	103	85	61	55	40
N	173	709	294	265	1424	314

Since it appears that most of the sulphate in Ontario lakes is derived from atmospheric input (with the exception of acid mine drainage lakes), a difference in the sulphate concentration of lakes is expected. Histograms of the sulphate concentrations found in each of the deposition zones are shown in Figure 7.7. There is a clear gradient in lake sulphate concentration from the lowest to the highest sulphur deposition zone.

The trends in alkalinity are the inverse of those observed for sulphate. The low sulphur deposition zones have higher alkalinity than those in the high sulphur deposition zones. This is partly due to the greater proportion of hardwater lakes in these zones, but is also a result of the replacement of alkalinity by sulphate. The distribution of lake alkalinity for each of the sulphur deposition zones is shown in Figure 7.8.

There is also a trend towards lower organic anion concentrations in the higher sulphur deposition zones, shown in Figure 7.9. Part of this trend may be geographic.

Eilers *et al.* (1988) reported lakes in the Upper Midwest United States had significantly higher organic anion concentrations than those in the Northeast. The lakes in deposition zone 1 are at approximately the same longitude range as those in the Upper Midwest subpopulation of the Eastern Lake Survey. However, it should be noted that there was a long-term trend toward lower DOC concentration in an acidifying lake in Central Ontario (Dillon *et al.* 1987). The possibility that lower organic anion concentrations in higher sulphur deposition zones result from acidification cannot be excluded.

Chloride distributions within sulphur deposition zones showed evidence of bimodality. As discussed above, the likely cause of higher chloride concentrations in a few Ontario lakes is runoff from road salting operations. It should also be noted that although the sodium concentration in deposition zone 1 is higher than that in the other zones, there is no corresponding increase in the chloride concentration, indicating that the higher sodium is probably associated with geological influences. The distributions of chloride concentrations by zone are shown in Figure 7.10.

7.3.4 Conductivity

As reflected in the discussion on the distribution of cation and anion concentrations, there are significant ($p<0.001$) differences in ionic strength among lakes in different sulphur deposition zones. These are reflected in the conductivity distributions shown in Figure 7.11 and summarized in Table 7.6.

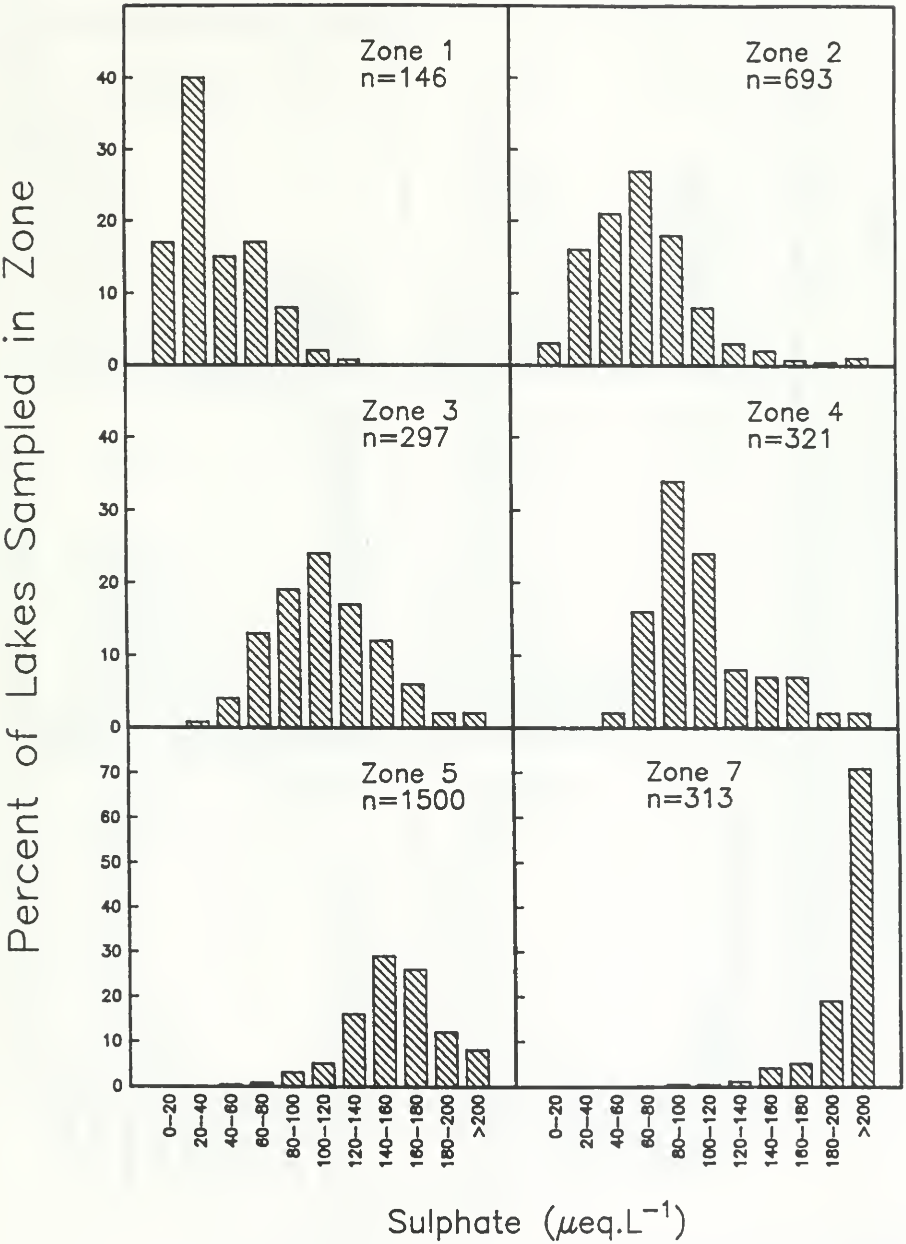

Figure 7.7: Sulphate distribution shown as percent of lakes sampled for each suphur deposition zone.

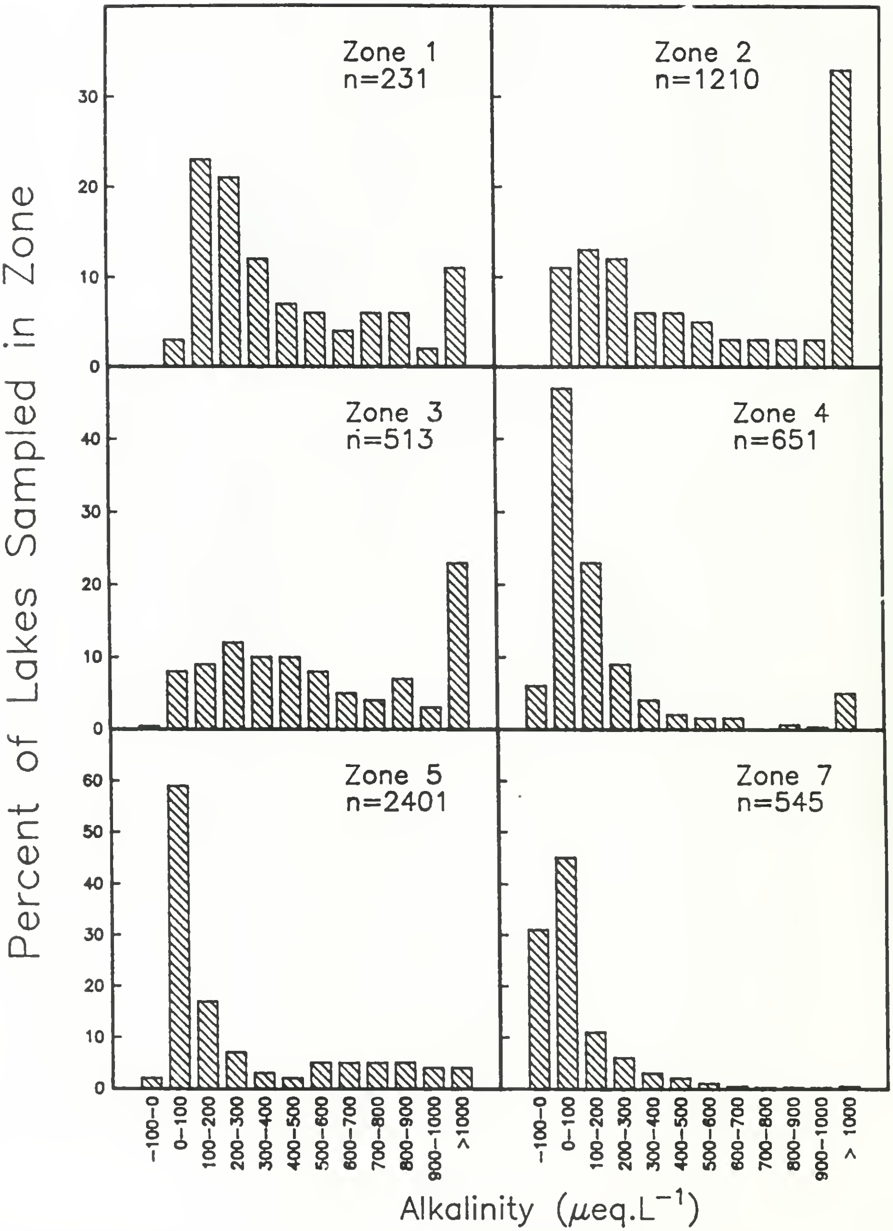

Figure 7.8: Alkalinity distribution shown as percent of lakes sampled for each suphur deposition zone.

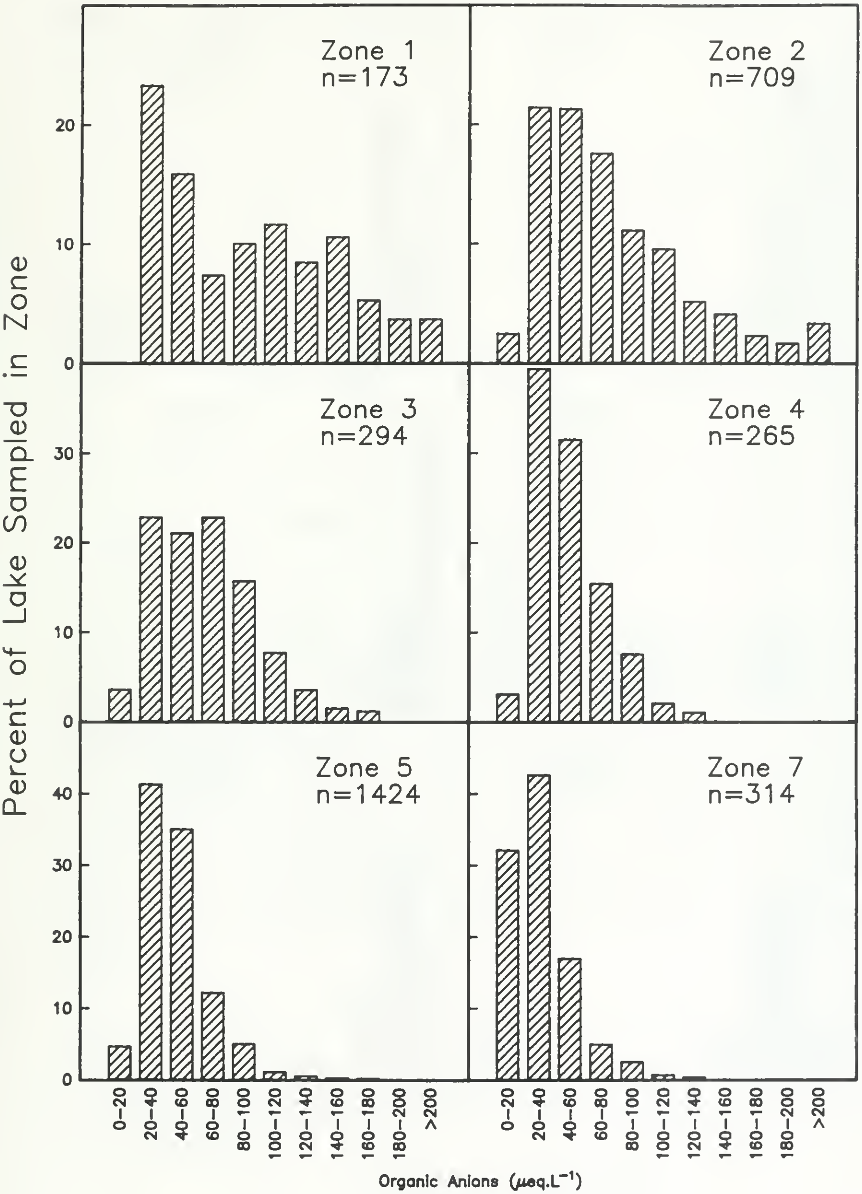

Figure 7.9: Organic anion distribution shown as percent of lake sampled for each sulphur deposition zone.

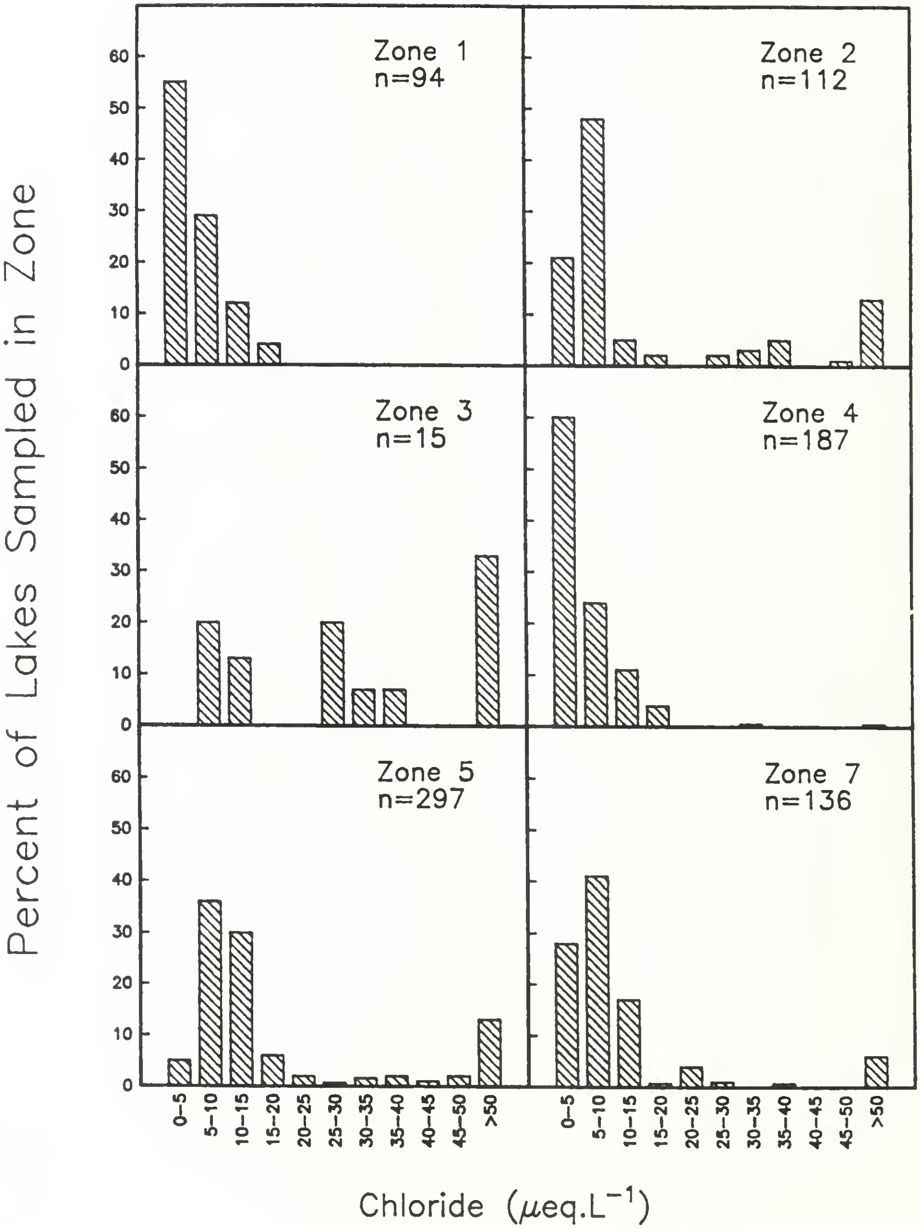

Figure 7.10: Chloride distribution shown as percent of lakes sampled for each suphur deposition zone.

Table 7.6: Summary of statistics for lake conductivity stratified by sulphur deposition zone

	S Deposition Zone					
	1	2	3	4	5	7
Conductivity						
Median	48	72	81	33	35	40
Q1	34	35	52	24	29	35
Q3	80	138	115	44	44	52
N	205	1148	444	608	2330	533

7.4 Lake Water Chemistry Stratified by Conductivity Class and Sulphur Deposition Zone

Many of the observed differences between sulphur deposition zones reflect a variations in the inherent nature of the lakes rather than effects of sulphur deposition. In particular, the ionic strength of the lakes (as estimated by conductivity) changes significantly ($p<0.001$) from zone to zone. If a fixed amount of sulphate replaces an equivalent amount of alkalinity in a lake, the effect will be quite different depending on the original ionic strength of the water in the lake. In a dilute lake, the sulphate may replace all of the available alkalinity, and an acid lake will result. In a lake with high ionic strength and large amounts of alkalinity, the same amount of sulphate may have a negligible effect.

In order to account for some of these effects, the data was stratified into three conductivity classes. These were arbitrarily chosen as ≤ 50 μS, 50-100 μS, and ≥ 100 μS. For convenience, these strata will be referred to as low, medium, and high conductivity lakes, respectively.

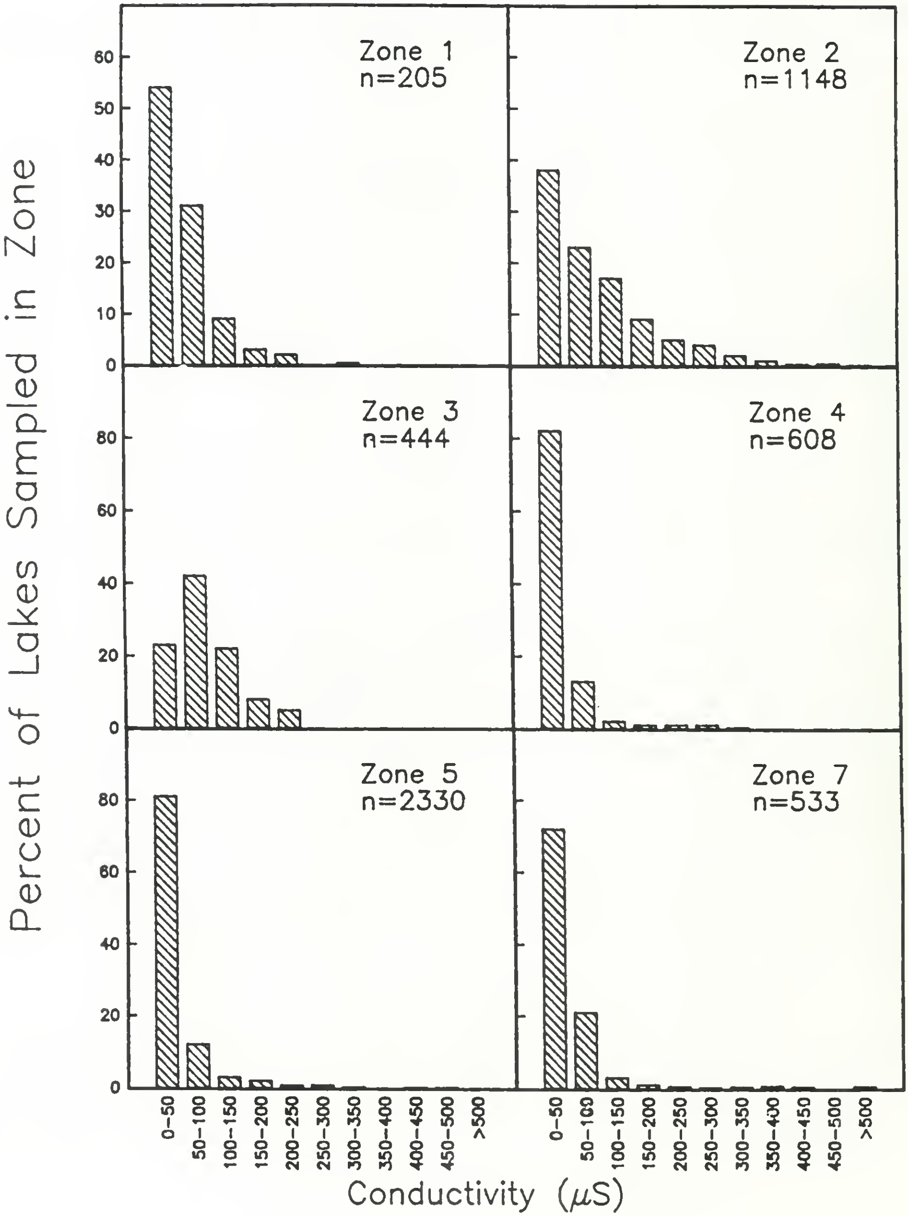

Figure 7.11: Conductivity distribution shown as percent of lakes sampled for each suphur deposition zone.

7.4.1 Lake Size

Variations in lake size within conductivity strata and between deposition zones are significant ($p<0.001$). In all of the conductivity strata, the lakes sampled in zone 1 are much larger than in the other zones. The effect that this has on the observations presented is examined in Section 7.5, where the lakes are stratified by size category.

Table 7.7: Lake size statistics by conductivity class and deposition zone.

	S Deposition Zone					
	1	2	3	4	5	7
Low Conductivity (< 50 μS)						
Median	324.1	145.0	29.8	34.9	25.4	48.1
Q1	139.0	43.0	9.0	11.5	11.4	12.8
Q3	891.0	386.2	29.8	91.3	79.6	300.3
N	111	441	103	498	1897	385
Medium Conductivity (50-100 μS)						
Median	393.1	143.9	81.5	76.9	42.8	87.8
Q1	96.0	40.3	26.5	38.8	17.2	35.4
Q3	988.6	483.2	173.0	179.0	140.3	300.3
N	63	262	186	76	289	114
High Conductivity (> 100 μS)						
Median	257.0	79.2	62.9	57.4	41.4	51.3
Q1	160.0	23.0	17.0	6.9	13.3	19.9
Q3	1307.0	220.1	151.0	624.4	153.2	243.5
N	31	445	155	34	144	34

7.4.2 Cations

The statistics for cations in the three conductivity classes are presented in Tables 7.8 to 7.10 in the low conductivity class, there is a trend to lower pH with higher sulphur deposition (Figure 7.12). In the other conductivity classes, the highest pH is in deposition zone 3, with declines in pH in zones 4, 5, and 7. Since pH can be strongly influenced by the degree of CO_2 saturation at the time of sampling, alkalinity is a more useful measure of the extent of lake acidification than pH.

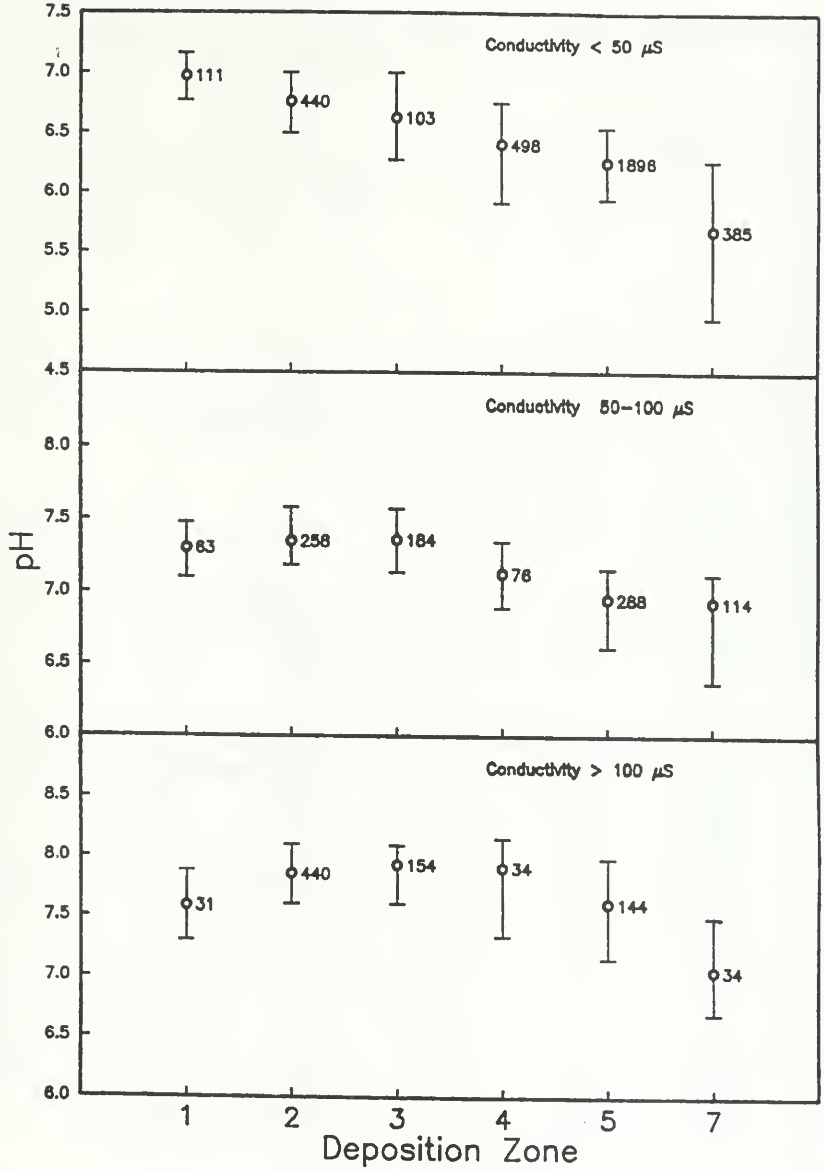

Figure 7.12: pH by conductivity class and deposition zone.

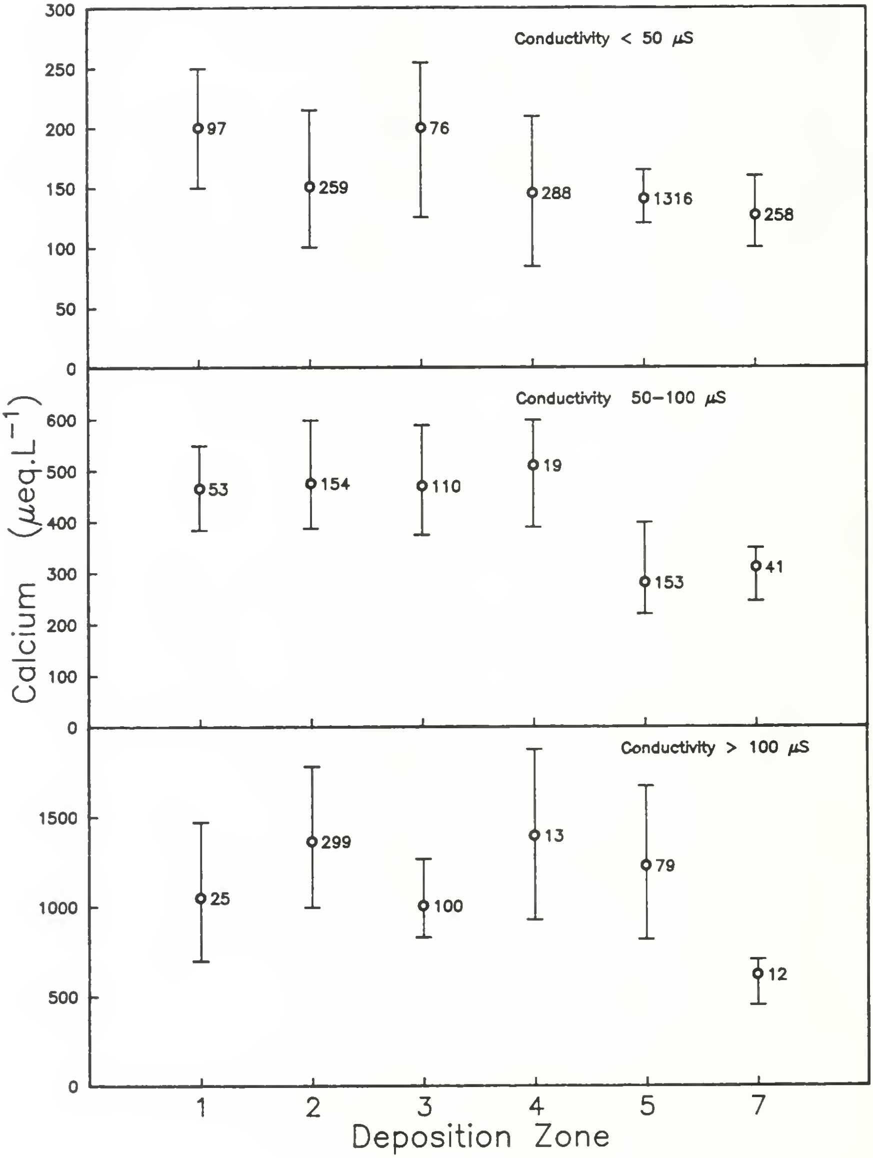

Figure 7.13: Calcium by conductivity class and deposition zone.

Calcium also shows a trend to lower values in higher deposition zones in low conductivity lakes. In medium conductivity lakes, zones 5 and 7 have lower calcium values than the other zones, while in the high conductivity class, only zone 7 is significantly different from the other zones (Figure 7.13). Part of these trends can be explained by the effect of differing conductivity depending on the anionic composition of the lake water in the different zones.

Table 7.8: Summary of cation statistics for low conductivity ($\leq$ 50 μS) lakes

	S Deposition Zone					
	1	2	3	4	5	7
pH						
Median	6.97	6.76	6.62	6.40	6.25	5.68
Q1	6.77	6.49	6.27	5.91	5.94	4.95
Q3	7.16	7.00	7.00	6.75	6.54	6.27
N	111	400	103	498	1896	385
Ca						
Median	199.6	149.7	199.6	144.7	139.7	126.0
Q1	149.7	99.8	124.8	83.8	119.8	99.8
Q3	249.5	214.6	254.5	209.6	164.7	159.7
N	97	259	76	288	1316	258
Mg						
Median	82.2	82.2	64.1	42.4	61.7	61.7
Q1	82.2	61.7	46.1	30.4	49.3	49.3
Q3	90.5	82.2	94.6	60.0	77.3	76.9
N	97	258	75	288	1225	258
Na						
Median	48.3	35.6	26.8	23.3	33.0	30.8
Q1	36.5	26.8	22.0	16.7	26.4	26.4
Q3	52.7	43.9	35.2	30.8	40.4	35.6
N	97	251	63	249	1129	245
K						
Median	14.6	11.0	6.1	5.9	11.5	10.2
Q1	11.3	8.4	4.3	4.1	9.7	8.2
Q3	16.9	14.1	9.0	8.2	14.3	12.8
N	97	255	62	203	1129	245

Table 7.9: Summary of cation statistics for medium conductivity (50-100 μS) lakes

	S Deposition Zone					
	1	2	3	4	5	7
pH						
Median	7.30	7.35	7.36	7.13	6.95	6.93
Q1	7.10	7.19	7.14	6.89	6.62	6.38
Q3	7.48	7.59	7.58	7.35	7.16	7.13
N	63	258	184	76	288	114
Ca						
Median	464.1	474.0	469.1	509.0	279.4	309.4
Q1	384.2	386.7	374.3	389.2	219.6	244.5
Q3	548.9	598.8	588.8	598.8	399.2	349.3
N	53	154	110	19	153	41
Mg						
Median	164.5	164.5	176.4	139.8	129.9	135.7
Q1	131.6	94.6	135.7	64.1	88.4	116.0
Q3	222.0	227.8	208.1	156.3	162.0	153.0
N	53	156	110	19	138	41
Na						
Median	43.5	39.6	35.2	42.2	70.3	50.1
Q1	33.8	30.3	28.8	30.8	50.5	39.3
Q3	57.1	52.7	42.4	44.4	126.6	76.0
N	53	149	100	16	111	32
K						
Median	14.6	13.3	9.2	13.2	17.9	14.7
Q1	10.7	9.5	7.4	7.8	13.8	10.2
Q3	18.9	16.9	10.7	14.1	22.8	17.9
N	53	155	98	14	111	32

Table 7.10: Summary of cation statistics for high conductivity ($\geq$ 100 μS) lakes

	S Deposition Zone					
	1	2	3	4	5	7
pH						
Median	7.58	7.85	7.93	7.90	7.60	7.04
Q1	7.30	7.60	7.60	7.33	7.15	6.69
Q3	7.88	8.10	8.09	8.15	7.98	7.50
N	31	440	154	34	144	34
Ca						
Median	1047.9	1362.3	1000.5	1392.2	1222.6	613.8
Q1	698.6	993.0	825.8	923.2	813.4	447.9
Q3	1472.1	1781.4	1265.0	1876.2	1671.6	703.6
N	25	299	100	13	79	12
Mg						
Median	370.1	495.9	335.5	296.1	254.5	242.6
Q1	304.3	371.3	272.2	242.6	163.7	193.3
Q3	483.6	656.3	388.2	433.4	408.3	312.1
N	25	298	100	12	78	12
Na						
Median	37.4	39.6	41.8	50.1	54.9	290.1
Q1	30.8	29.0	33.2	44.4	33.0	121.7
Q3	70.3	59.3	46.1	54.1	189.0	1399.7
N	25	287	92	12	69	8
K						
Median	20.7	15.3	12.3	22.8	25.8	26.3
Q1	12.8	10.7	9.7	18.2	19.4	13.8
Q3	24.8	21.5	15.9	33.0	32.0	42.2
N	25	289	92	12	69	8

Magnesium shows trends toward lower values as sulphur deposition increases in all conductivity classes (see Figure 7.14). In the low conductivity class, zone 4 has the lowest magnesium values.

In low conductivity lakes, zone 1 has the highest median sodium levels (Figure 7.15). This may be a reflection of higher sodium concentrations in the bedrock in northwestern Ontario, as discussed above. Otherwise, zone 5 generally has the highest sodium values across the different conductivity classes. This is probably a reflection of higher densities of population and roads in this zone. The exception is the high conductivity lakes in zone 7. Because these lakes also have very high chloride (Figure 7.20) they are undoubtedly road salt lakes and are misclassified through artificially high conductivity contributed by the road salt.

Potassium appears to be consistently lowest in zone 3, in all of the conductivity classes (Figure 7.16). This may be attributed to differences in the potassium content of the bedrock in this area, but this cannot be confirmed with available data.

7.4.3 Anions

The deposition zone statistics for the anions in the three conductivity strata are presented in Tables 7.11, 7.12, and 7.13. In general, the anionic composition of water in Ontario lakes appears to be much more affected by sulphur deposition than the cations. The sulphate content of Ontario lake water, regardless of conductivity class, increases with sulphur deposition (Figure 7.17). This is entirely consistent with the hypothesis that atmospheric sulphate deposition is the primary source of sulphate in Ontario lakes. In the northwest, sulphate is a trace anion, usually less than 50 $\mu eq.L^{-1}$. In the higher deposition zones, it represents the dominant anion.

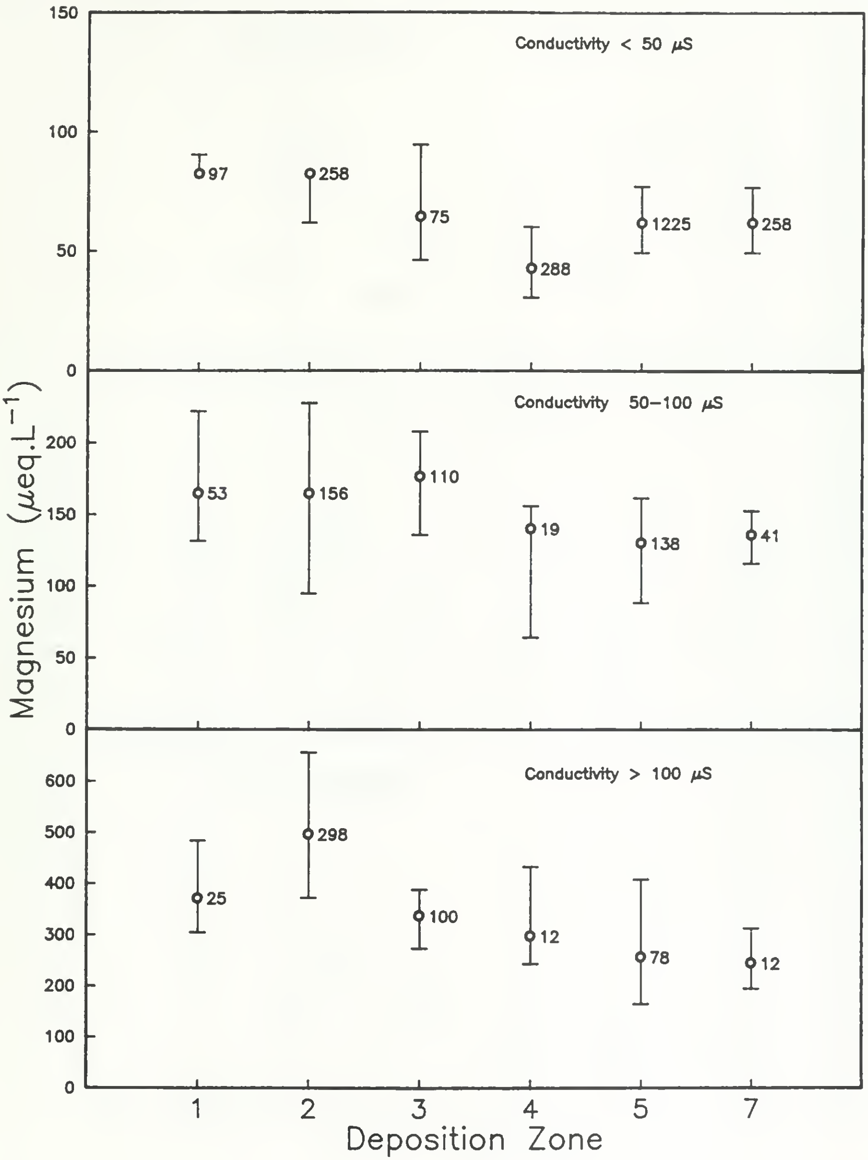

Figure 7.14: Magnesium by conductivity class and deposition zone.

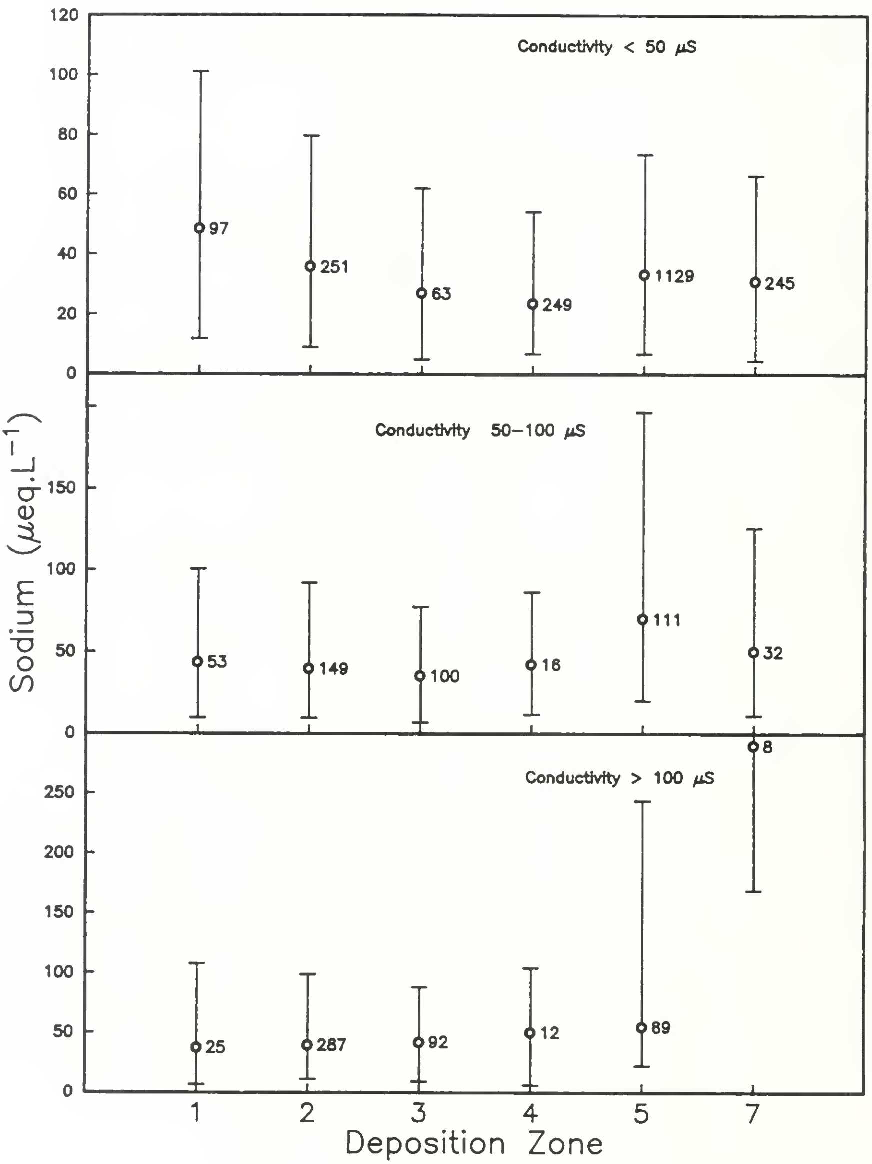

Figure 7.15: Sodium by conductivity class and deposition zone.

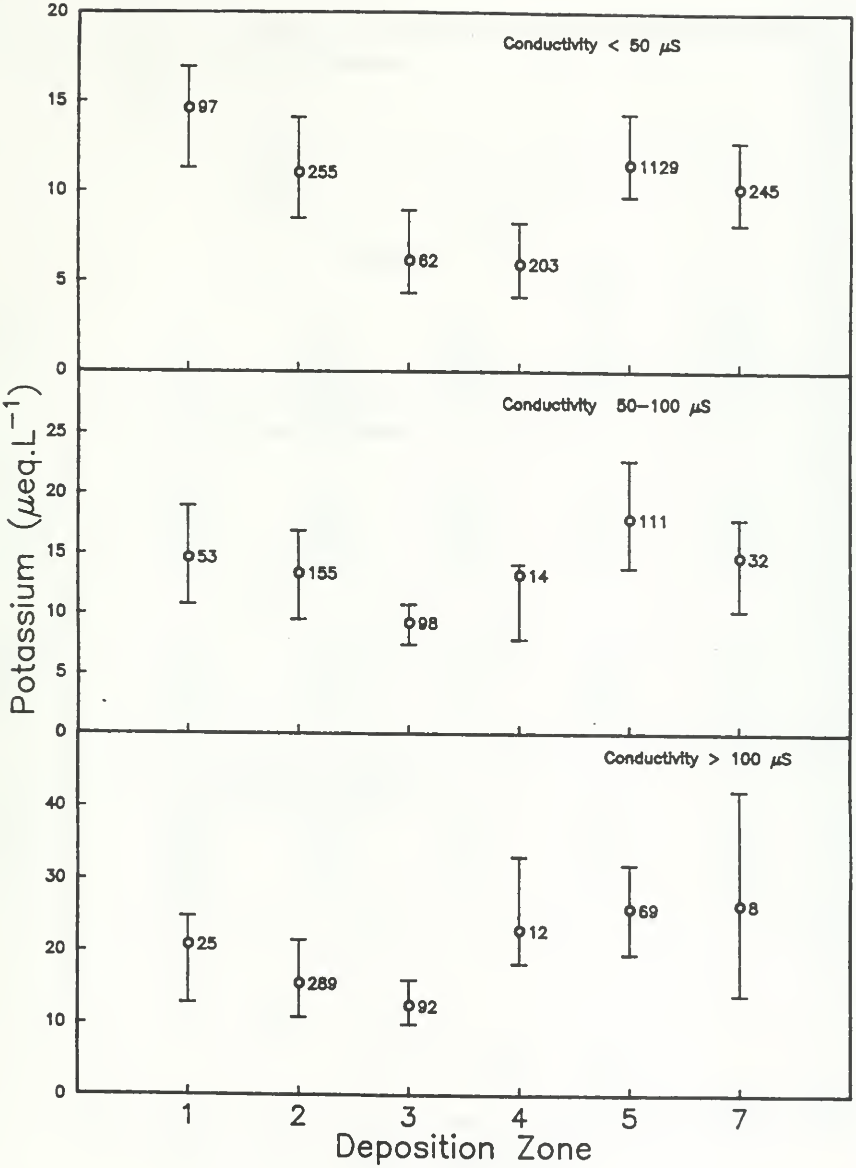

Figure 7.16: Potassium by conductivity class and deposition zone.

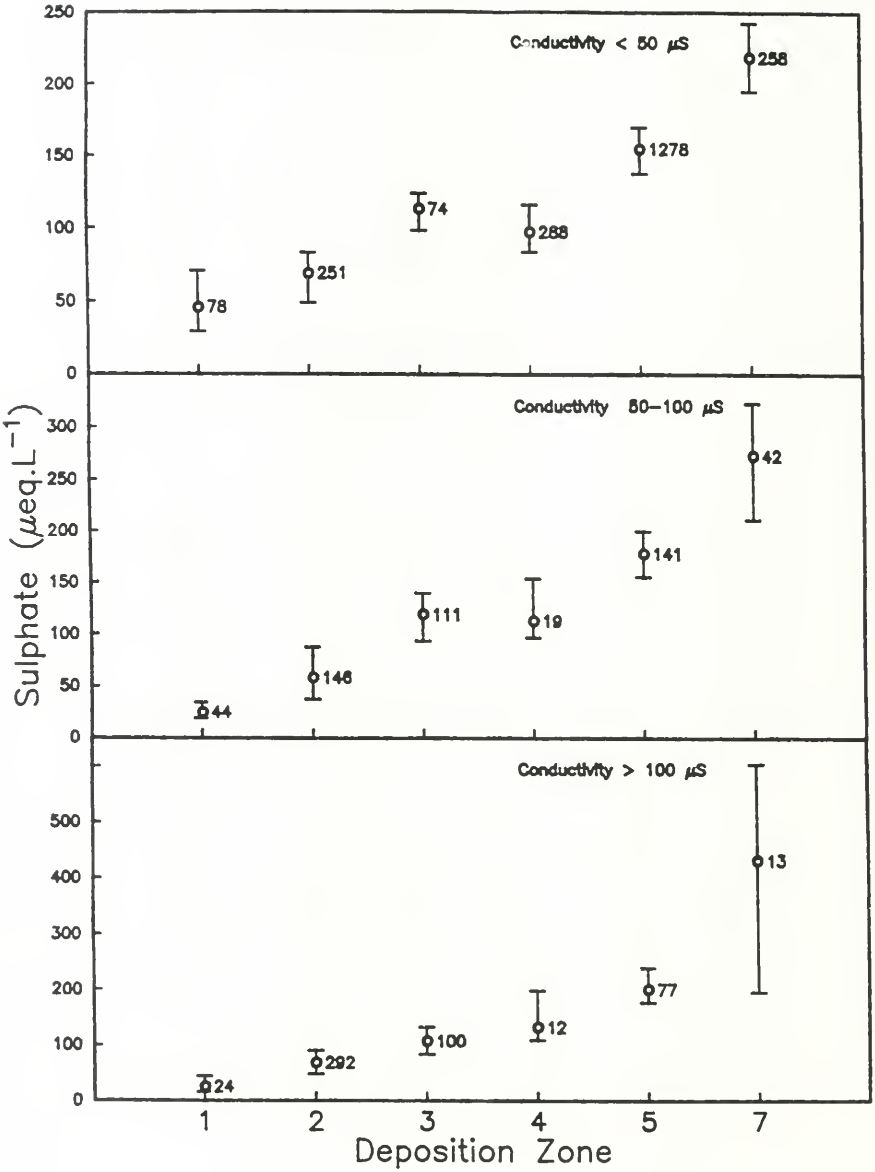

Figure 7.17: Sulphate by conductivity class and deposition zone.

Table 7.11: Summary of anion statistics for low conductivity (≤ 50 μS) lakes

	S Deposition Zone					
	1	2	3	4	5	7
SO_4						
Median	45.7	69.1	113.3	97.4	154.9	218.6
Q1	29.1	48.7	98.4	83.5	137.6	194.9
Q3	70.8	83.3	124.0	116.2	169.7	242.5
N	78	251	74	288	1278	258
Alk						
Median	220.0	153.4	128.0	70.6	61.1	8.0
Q1	164.0	94.2	62.6	27.8	33.0	-9.8
Q3	275.6	236.0	206.6	134.0	101.3	42.6
N	111	441	101	495	1878	375
Cl						
Median	2.8	5.6	7.9	3.1	10.2	6.5
Q1	0.1	2.8	5.4	1.7	8.2	4.5
Q3	2.8	8.5	14.4	8.2	13.5	10.2
N	39	47	3	179	248	121
A^-						
Median	52.8	57.8	51.4	44.0	40.6	6.5
Q1	34.4	41.9	38.5	31.9	31.1	4.5
Q3	109.2	84.6	68.4	60.8	53.6	10.2
N	96	257	74	236	1186	121

Table 7.12: Summary of anion statistics for medium conductivity (50-100 μS) lakes

	S Deposition Zone					
	1	2	3	4	5	7
SO_4						
Median	24.5	58.2	119.1	112.6	178.0	272.7
Q1	18.9	37.6	93.5	96.4	155.5	211.3
Q3	34.2	87.4	140.1	154.0	199.8	322.6
N	44	146	111	19	141	42
Alk						
Median	572.0	546.0	454.7	365.4	259.0	166.0
Q1	474.0	428.0	318.4	223.4	162.0	88.0
Q3	734.0	716.0	618.1	513.5	371.4	251.0
N	63	257	182	76	281	113
Cl^-						
Median	5.6	8.5	33.8	11.3	70.5	15.5
Q1	2.8	5.6	25.4	8.5	39.5	7.1
Q3	8.5	8.5	67.7	59.2	170.6	163.6
N	38	41	11	3	23	11
A^-						
Median	119.5	68.3	78.1	49.0	46.6	34.6
Q1	69.7	39.3	60.3	38.4	34.3	23.7
Q3	158.3	112.6	101.2	64.9	57.8	52.8
N	543	153	109	17	123	40

Table 7.13: Summary of anion statistics for high conductivity (≥ 100 μS) lakes

	S Deposition Zone					
	1	2	3	4	5	7
SO_4^{2-}						
Median	24.6	68.1	107.1	131.7	199.8	430.9
Q1	15.6	48.4	83.6	108.3	176.3	194.6
Q3	44.3	90.2	132.5	197.8	238.6	603.7
N	24	292	100	12	77	13
Alk						
Median	1240.0	1595.0	1213.7	1552.6	1134.5	329.3
Q1	930.0	1179.6	916.2	1075.2	625.6	120.8
Q3	1836.0	2296.0	1530.4	2188.0	1832.0	525.4
N	31	438	154	33	142	34
Cl^-						
Median	5.6	36.7	36.7	16.9	53.6	782.7
Q1	2.8	9.9	36.7	14.1	14.1	90.4
Q3	14.1	57.8	36.7	19.7	155.1	1775.6
N	17	24	1	5	26	4
A^-						
Median	118.2	76.5	56.8	42.8	48.6	36.4
Q1	84.6	44.9	32.9	20.4	37.8	29.4
Q3	161.6	112.7	83.5	73.7	62.1	42.4
N	24	295	99	12	70	14

Alkalinity follows consistent trends opposite to that of sulphate (Figure 7.18). Again, these observations are entirely consistent with a simple alkalinity titration model of lake acidification resulting from atmospheric sulphate deposition. A portion of these trends within the individual conductivity strata can be attributed to the use of conductivity as a classification variable, but these effects are minimal compared to the alkalinity depletion associated with sulphate input. In the high conductivity class, the trend is not as clear as the lower classes because this strata is open ended, and includes some extremely bicarbonate dominated high conductivity lakes in zones 2 and 4.

The organic anion content of lakes shows a consistent trend toward lower concentrations in the higher sulphur deposition zones (Figure 7.19). A temporal trend toward lower organic anion concentration has been observed during the acidification of an intensively studied lake in Central Ontario (Dillon *et al.* 1987), but the consistency of the drop in A^- in each of the conductivity classes argues for, at least in part, a geographic explanation for the observation.

Chloride shows no significant trends (Figure 7.20). The anomalously high values for chloride in the high conductivity class in zone 7, coupled with the high sodium and low calcium and magnesium indicates that these lakes are road salt lakes. The slightly higher chloride concentrations in zone 5 are also a road salt effect.

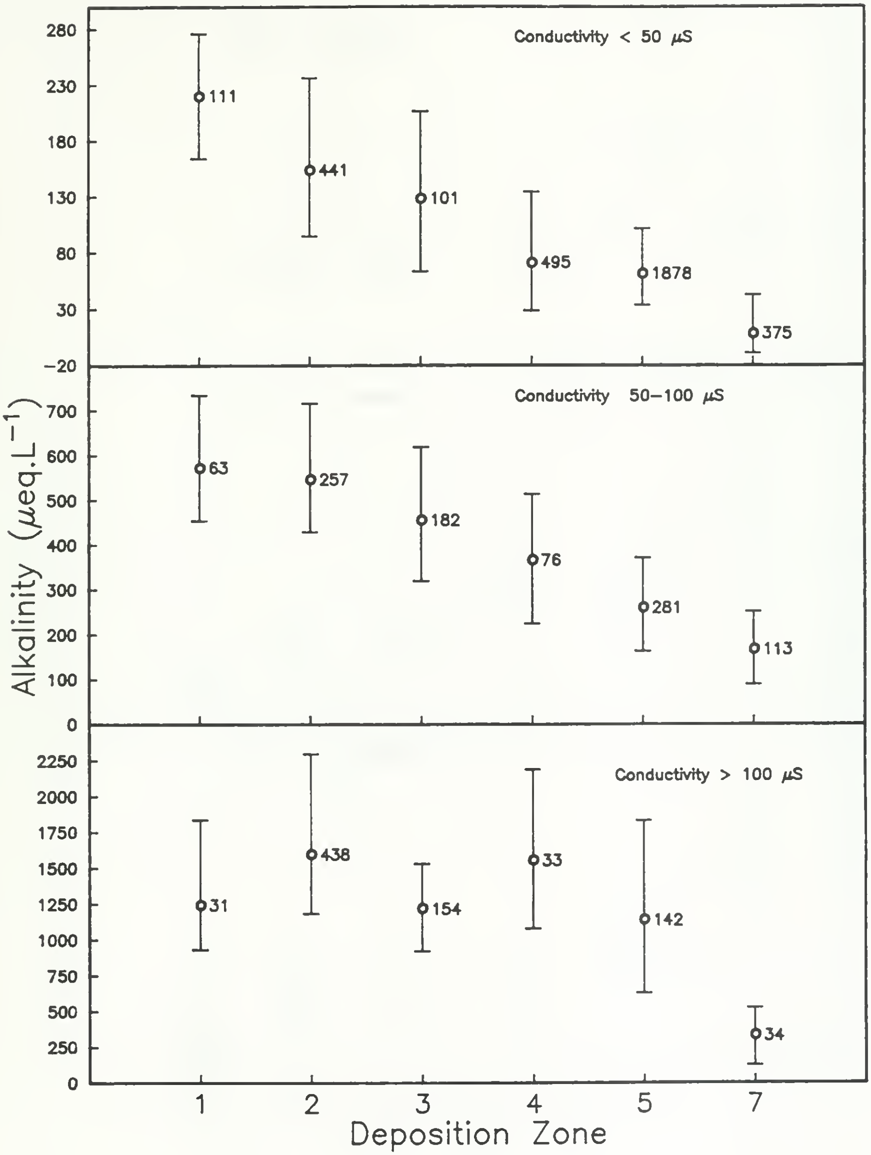

Figure 7.18: Alkalinity by conductivity class and deposition zone.

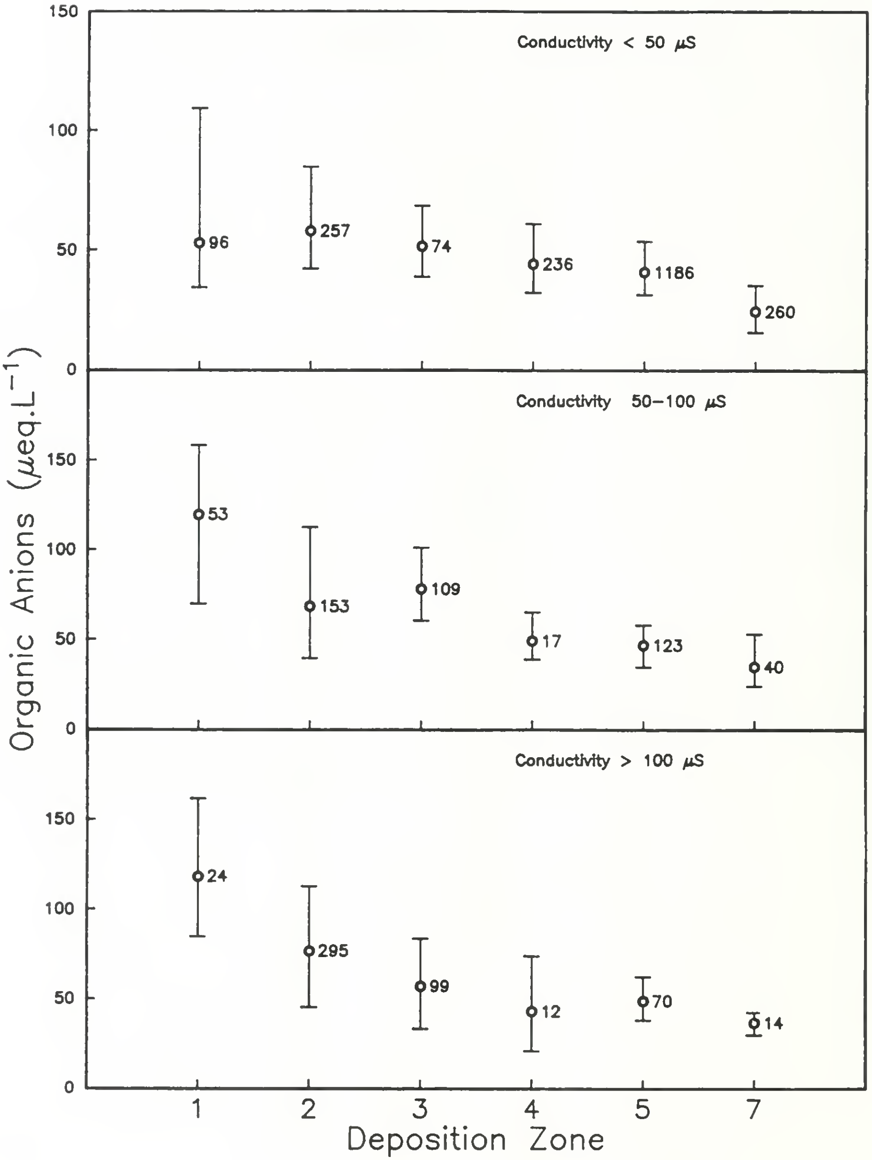

Figure 7.19: Organic anions by conductivity class and deposition zone.

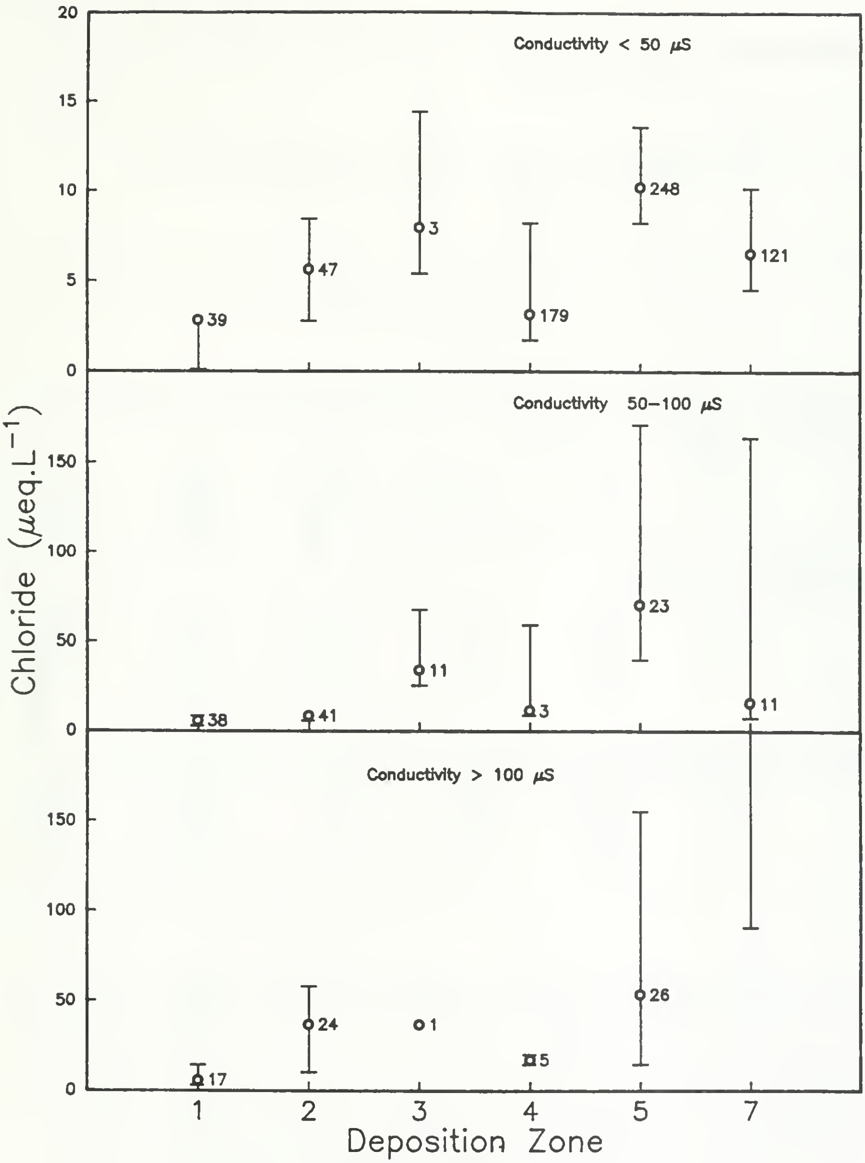

Figure 7.20: Chloride by conductivity class and deposition zone.

7.4.4 Conductivity

Table 7.14: Conductivity statistics for lakes in the three conductivity classes

	S Deposition Zone					
	1	2	3	4	5	7
Low conductivity (≤ 50 μS)						
Median	35.0	30.0	35.0	30.0	32.1	37.0
Q1	30.0	25.0	24.0	22.0	28.0	33.0
Q3	42.0	38.0	43.0	37.0	38.0	41.0
N	111	441	103	498	1897	385
Medium Conductivity (50-100 μS)						
Median	68.0	71.8	72.9	65.0	61.0	60.0
Q1	60.0	60.0	60.2	56.0	54.0	54.0
Q3	86.0	83.0	85.7	80.0	74.0	72.0
N	63	262	186	76	289	114
High Conductivity (≥ 100 μS)						
Median	127.0	167.0	133.0	185.5	158.0	167.5
Q1	112.0	125.0	114.0	142.5	126.4	120.5
Q3	182.0	228.0	168.0	230.0	212.0	315.0
N	31	445	155	34	144	34

Even within conductivity strata, there are significant differences in conductivity between the deposition zones (Tables 7.14, Figure 7.21). In the low conductivity stratum, zones 2 and 4 have the most dilute lakes, while zones 1, 3 and 7 have higher conductivity. These differences are statistically significant ($p<0.01$). In the medium conductivity stratum, the four lower sulphur deposition zones tend to have slightly higher conductivity. Again, these are significantly different ($p<0.05$). In the high conductivity stratum, zones 1 and 3 are significantly lower than the other zones.

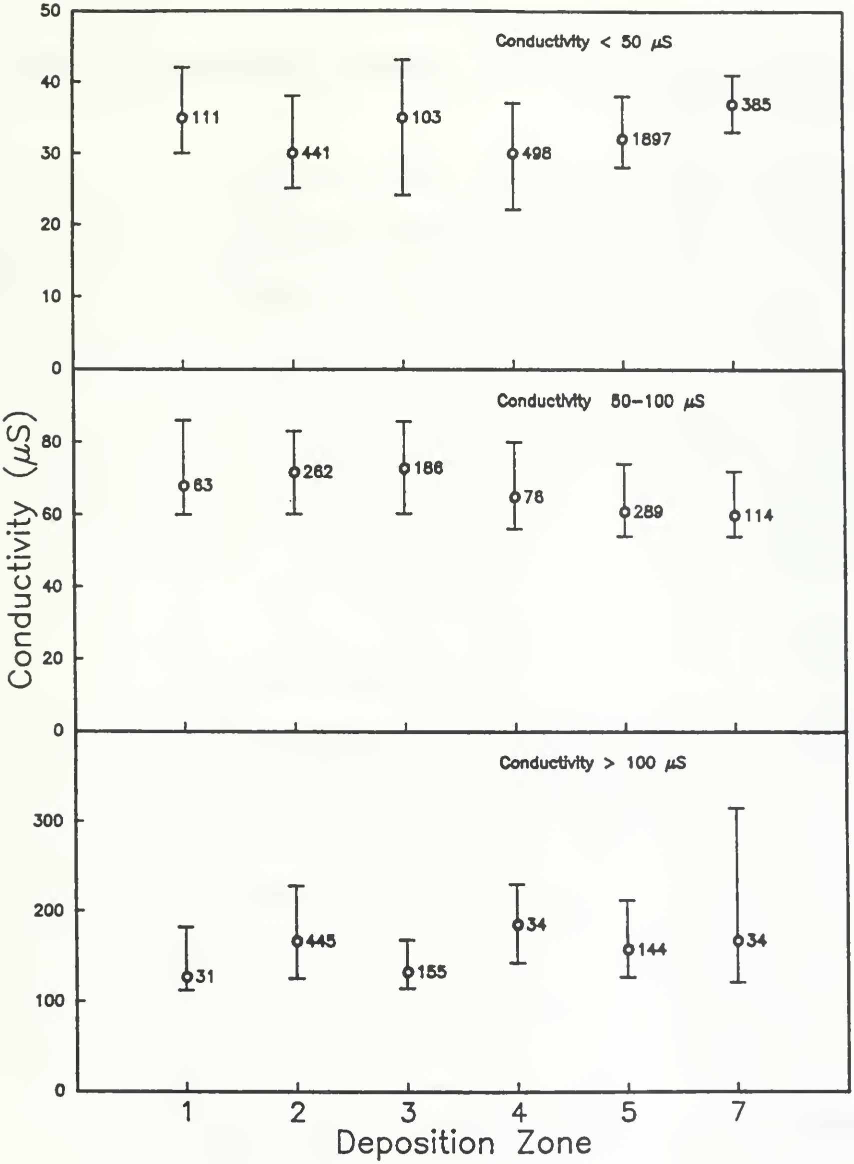

Figure 7.21: Conductivity by conductivity class and deposition zone.

7.5 Lake Water Chemistry Stratified by Lake Size, Conductivity Class and Sulphur Deposition Zone

Lakes of different size may respond at different rates to acid inputs. Typically, larger lakes have longer hydraulic retention times and on a simple hydrologic basis would be expected to respond more slowly than smaller lakes to an increase or decrease in acid loading. In most cases, larger lakes are not headwaters, and they derive much of their water from upstream lakes rather than the immediate watershed. The impacts of acid input are mediated by in lake processes in the upstream lakes and their watersheds (Schindler et al. 1987), resulting in a delayed response to acidification. The effect of lake size on acid sensitivity was examined by stratifying the sample into four size categories: 1000-999 ha, 100-999 ha, 10-99 ha, and 1-9.9 ha. These categories were chosen because there are population estimates for the total number of lakes in the province based on these size strata.

7.5.1 Cations

Measured pH within the sulphur deposition, conductivity, and lake size strata is shown in Figures 7.22 to 7.24. There is a consistent trend toward lower pH in smaller lakes in the low conductivity class, regardless of deposition zone. In the low deposition zones, the lower pH in the smaller lakes appears to be a function of higher organic anion concentrations (see 7.5.2). In the high sulphur deposition zones, there is no consistent trend to higher organic anion concentrations, and the pH trend indicates that small lakes have been more strongly acidified by sulphate inputs. It is likely that these smaller lakes had higher organic anion concentrations and lower alkalinity before the onset of anthropogenic acidification, and so are more strongly acidified because of lower initial acid buffering capacity. The differences in pH between size classes within deposition zone are significant ($p<0.01$) for low conductivity lakes.

The data for calcium, magnesium, sodium, and potassium have been combined and show that the smaller lakes tend to have significantly ($p<0.01$) lower total base cation

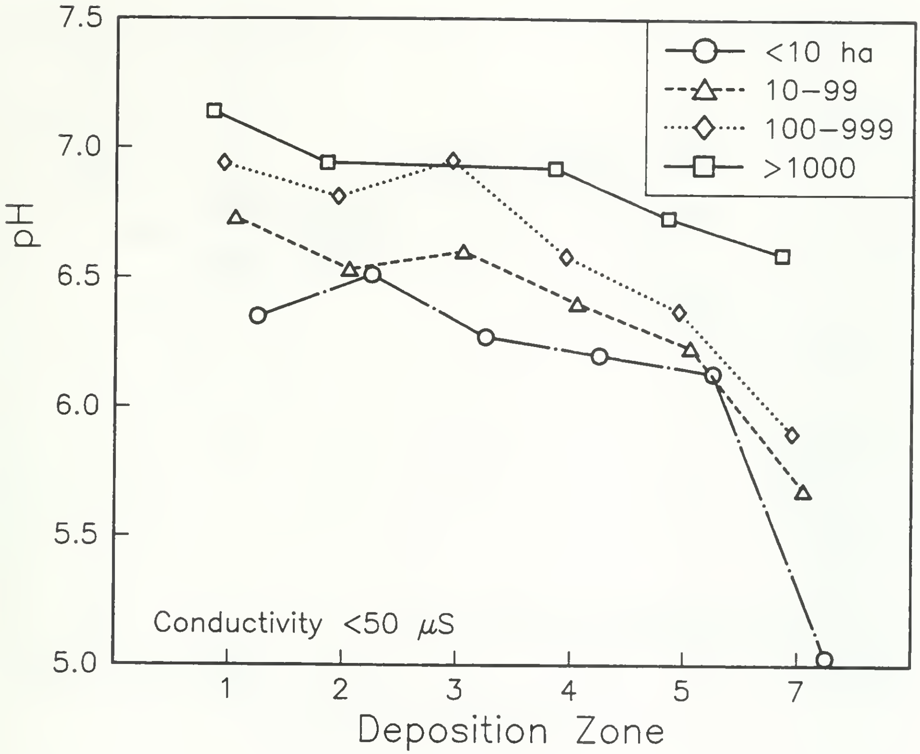

Figure 7.22: Relationship between S deposition (expressed at S deposition zone number) and mean pH for lakes with conductivity < 50 μS by lake size class.

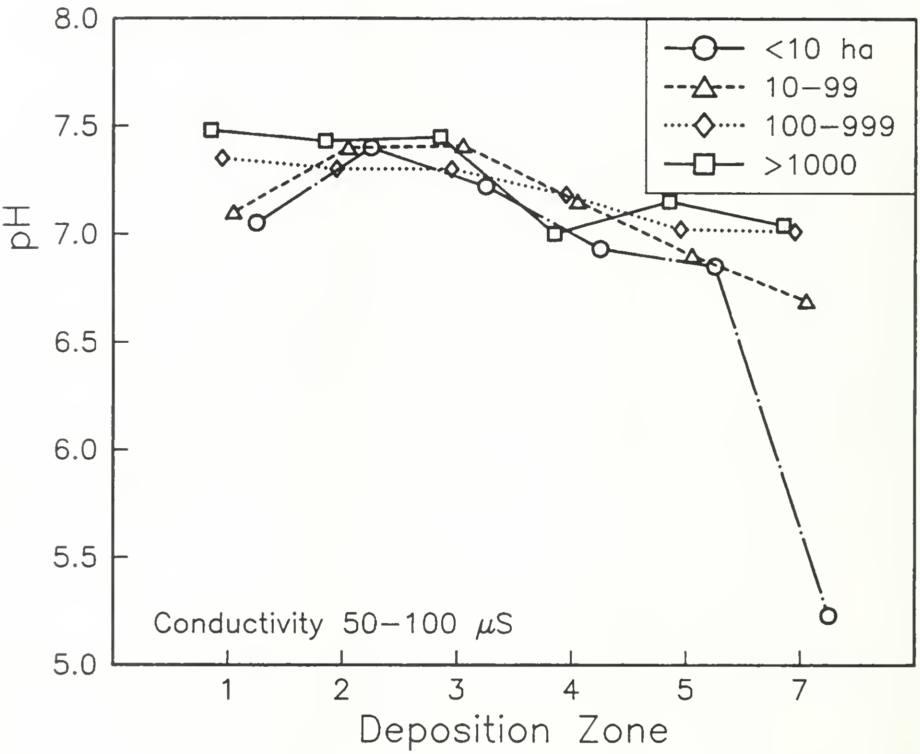

Figure 7.23: Relationship between S deposition (expressed at S deposition zone number) and mean pH for lakes with conductivity 50-100 μS by lake size class.

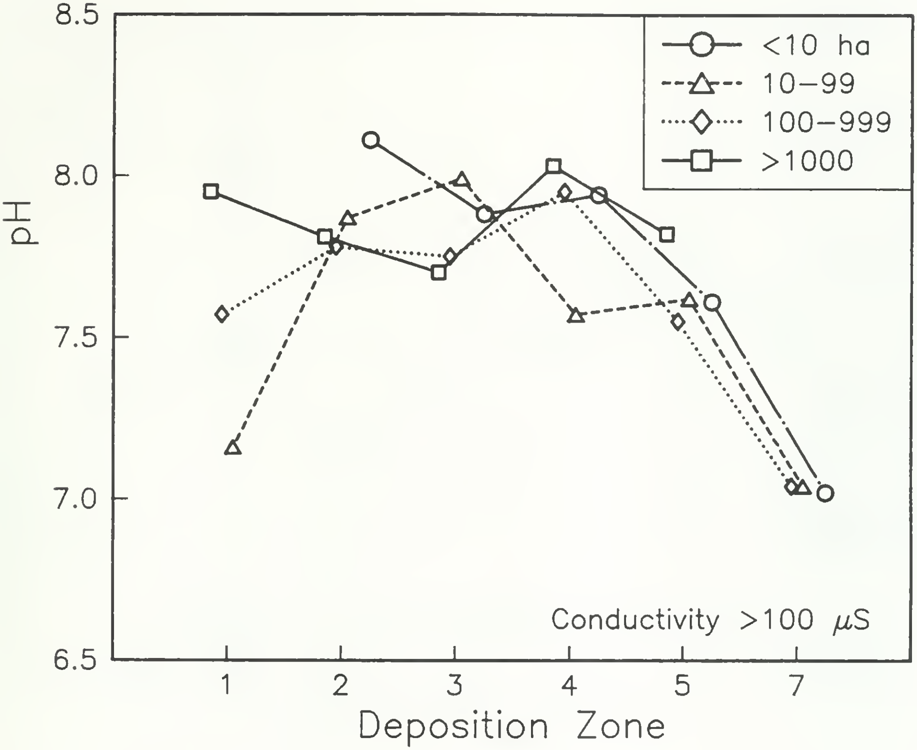

Figure 7.24: Relationship between S deposition (expressed at S deposition zone number) and mean pH for lakes with conductivity > 100 μS by lake size class.

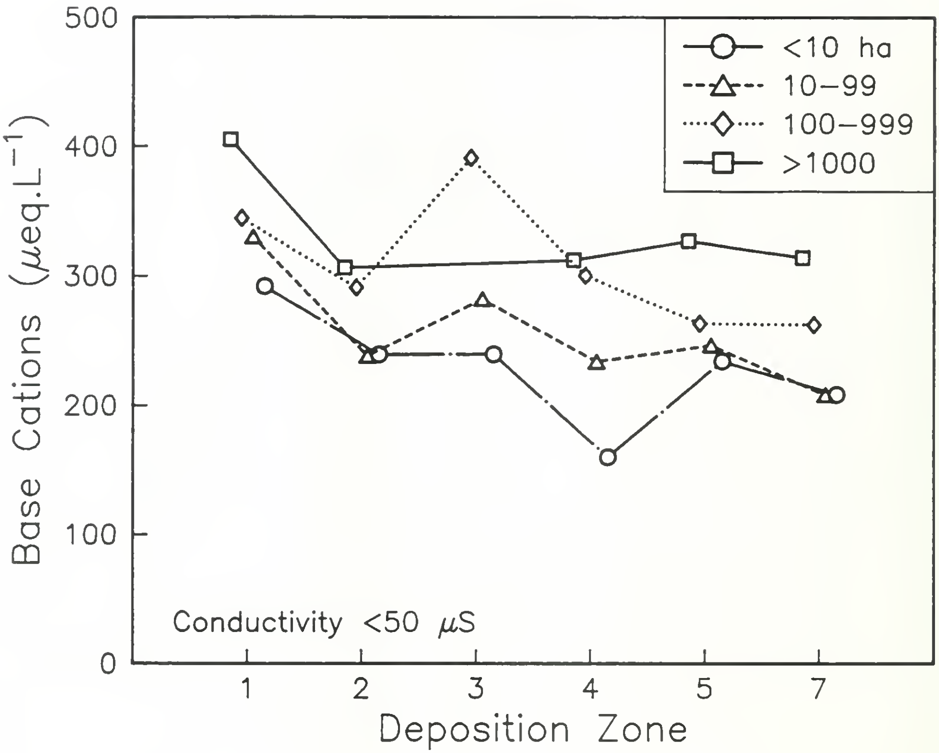

Figure 7.25: Relationship between S deposition (expressed at S deposition zone number) and mean base cations for lakes with conductivity < 50 by lake size class.

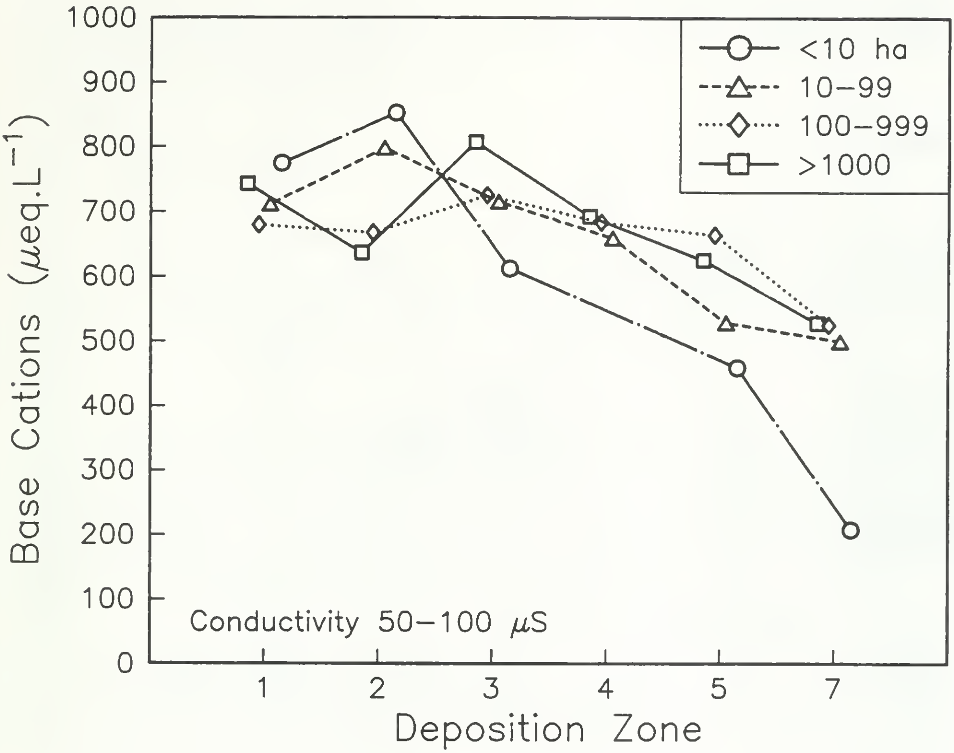

Figure 7.26: Relationship between S deposition (expressed at S deposition zone number) and mean base cations for lakes with conductivity 50-100 by lake size class.

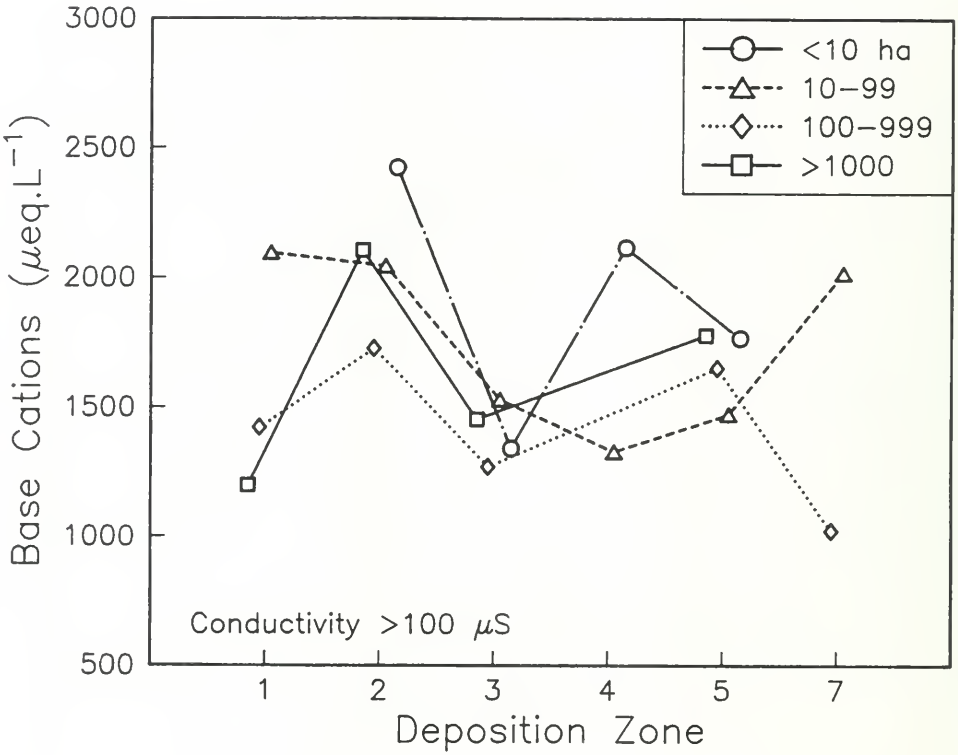

Figure 7.27: Relationship between S deposition (expressed at S deposition zone number) and mean base cations for lakes with conductivity > 100 by lake size class.

concentrations (Figures 7.25 to 7.27), regardless of conductivity stratum. This may be due to short retention times and to the fact that a greater proportion of water in the smaller lakes is derived from the immediate watershed. This is also reflected in lower conductivity, even within conductivity strata.

7.5.2 Anions

There is a significant ($p<0.01$) trend toward lower sulphate concentrations in smaller lakes (Figures 7.28 to 7.30) in the low conductivity stratum. Again, this is probably in keeping with the above discussion on rapid flushing of smaller bodies of water.

Lake alkalinity generally follows the same trend as lake pH. In the low conductivity stratum, smaller lakes have significantly ($p<0.05$) lower conductivity than the larger lakes with the exception of zone 5. In medium conductivity lakes, alkalinity differences between lake sizes are only significant ($p<0.05$) in the high deposition zones (5 and 7). In the high conductivity lakes, size is generally not a factor.

As noted above, organic anions tend to be higher in smaller lakes in the low sulphur deposition zones (Fig. 7.34 to 7.36). These differences are significant ($p<0.05$) for low conductivity lakes in all but zone 4. In medium conductivity lakes, significant ($p<0.05$) differences between lakes of different size appear only in zones 1 and 3 (where smaller lakes have higher A^-) and in zone 7, where smaller lakes have lower A^-. In high conductivity lakes, lakes size is not important.

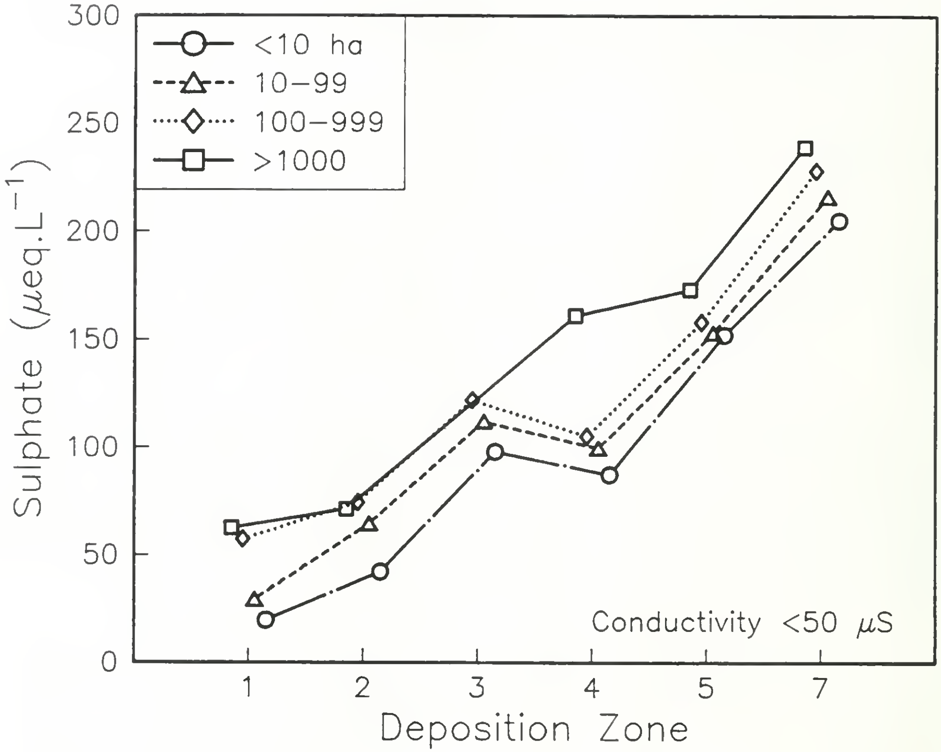

Figure 7.28: Relationship between S deposition (expressed at S deposition zone number) and mean sulphate for lakes with conductivity < 50 μS by lake size class.

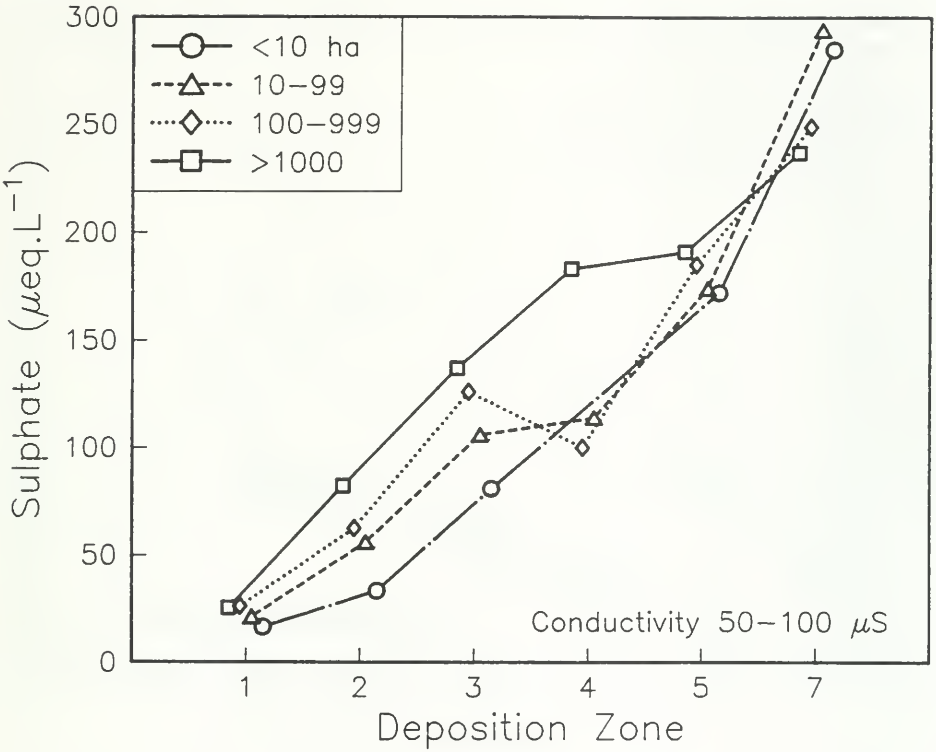

Figure 7.29: Relationship between S deposition (expressed at S deposition zone number) and mean sulphate for lakes with conductivity 50-100 μS by lake size class.

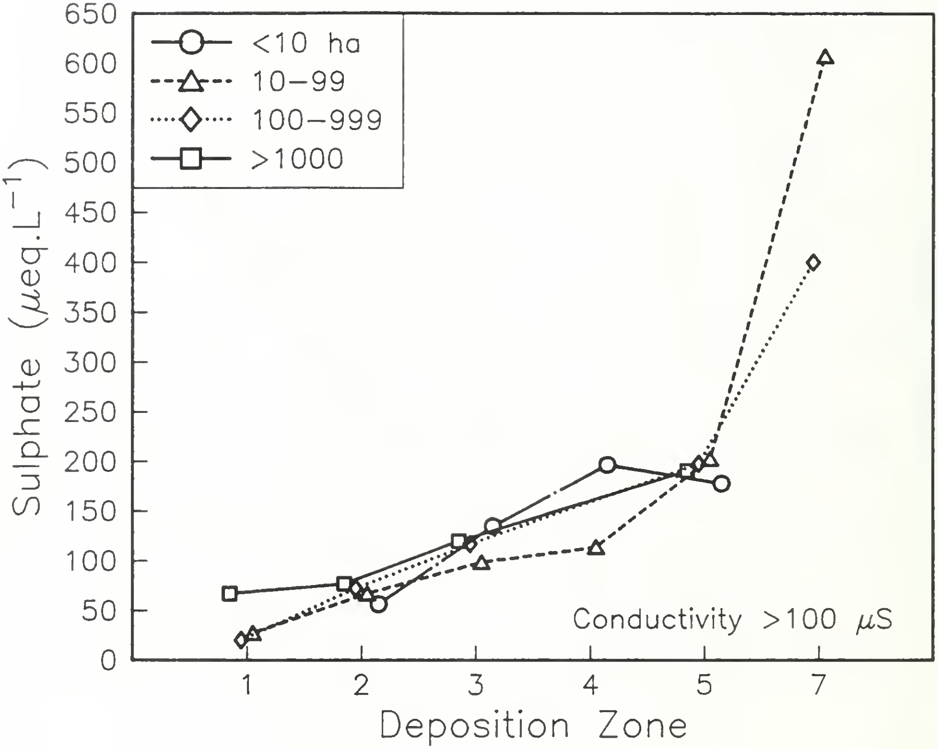

Figure 7.30: Relationship between S deposition (expressed at S deposition zone number) and mean sulphate for lakes with conductivity > 100 μS by lake size class.

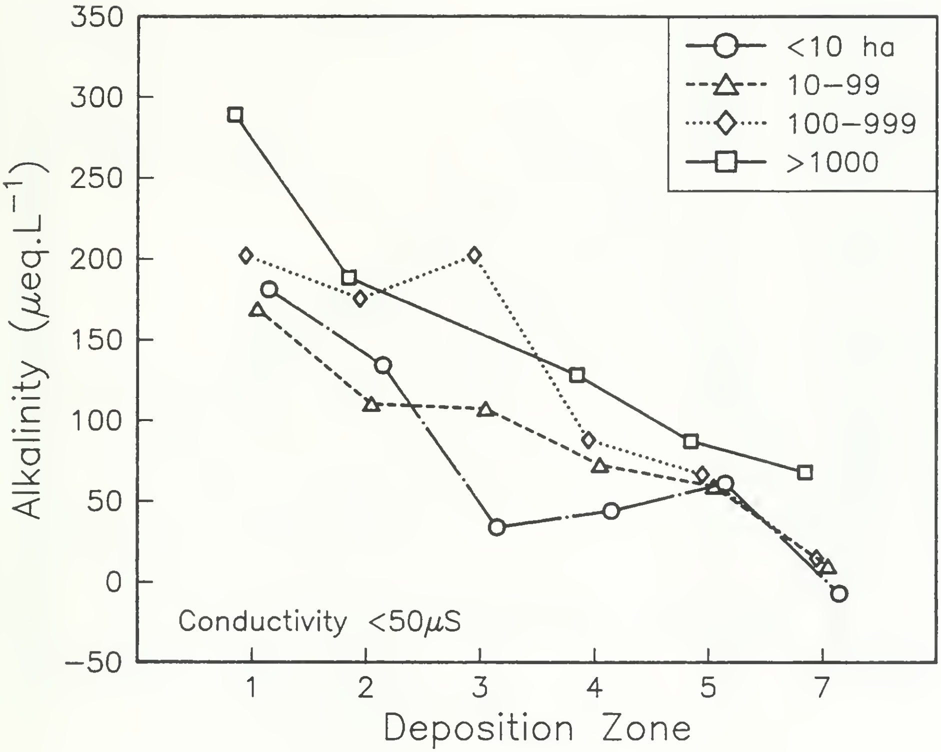

Figure 7.31: Relationship between S deposition (expressed at S deposition zone number) and mean alkalinity for lakes with conductivity < 50 μS by lake size class.

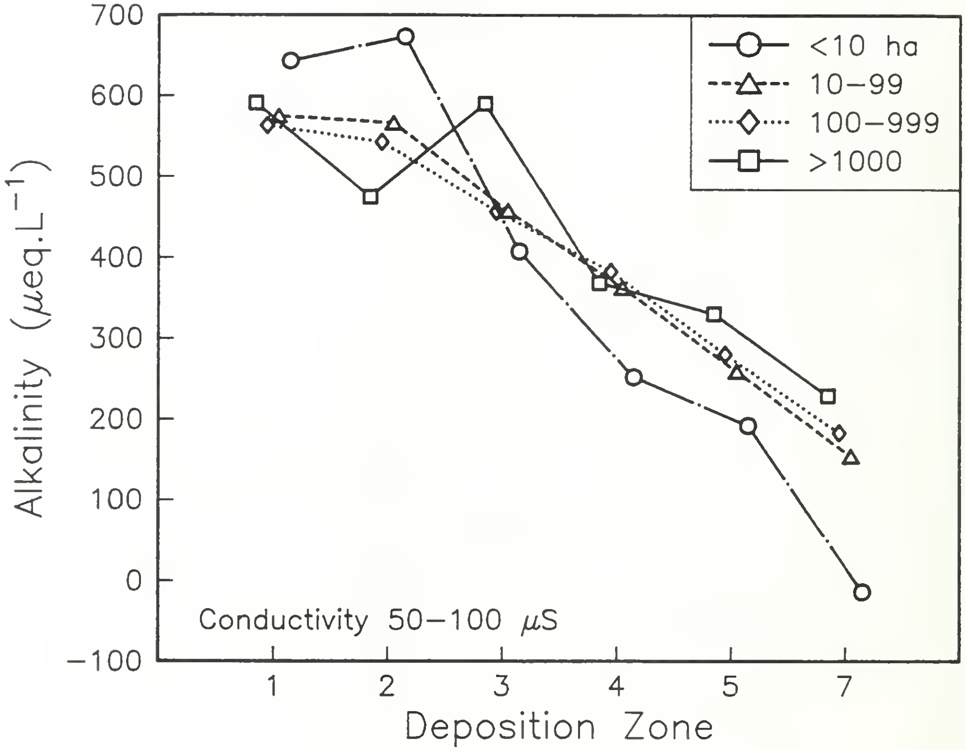

Figure 7.32: Relationship between S deposition (expressed at S deposition zone number) and mean alkalinity for lakes with conductivity 50-100 μS by lake size class.

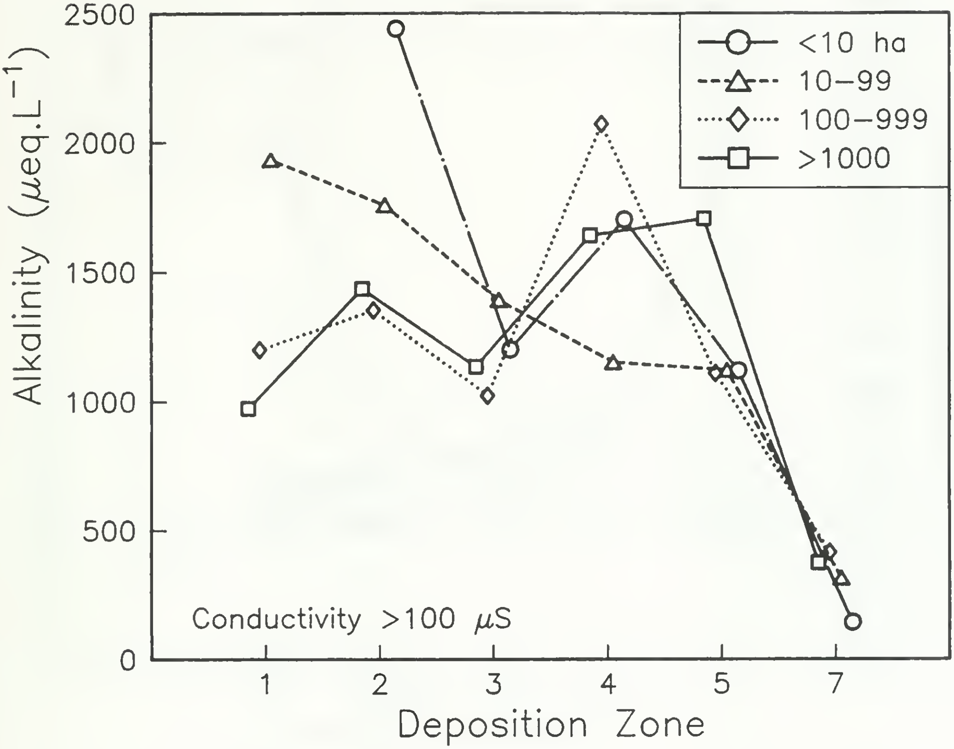

Figure 7.33: Relationship between S deposition (expressed at S deposition zone number) and mean alkalinity for lakes with conductivity > 100 μS by lake size class.

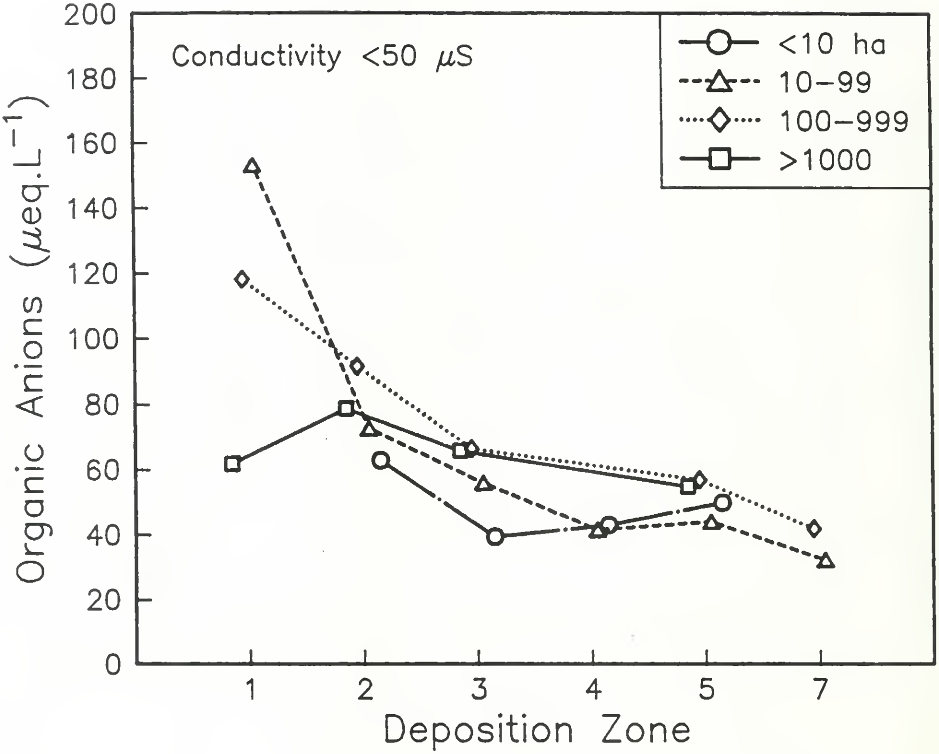

Figure 7.34: Relationship between S deposition (expressed at S deposition zone number) and mean organic anions for lakes with conductivity < 50 μS by lake size class.

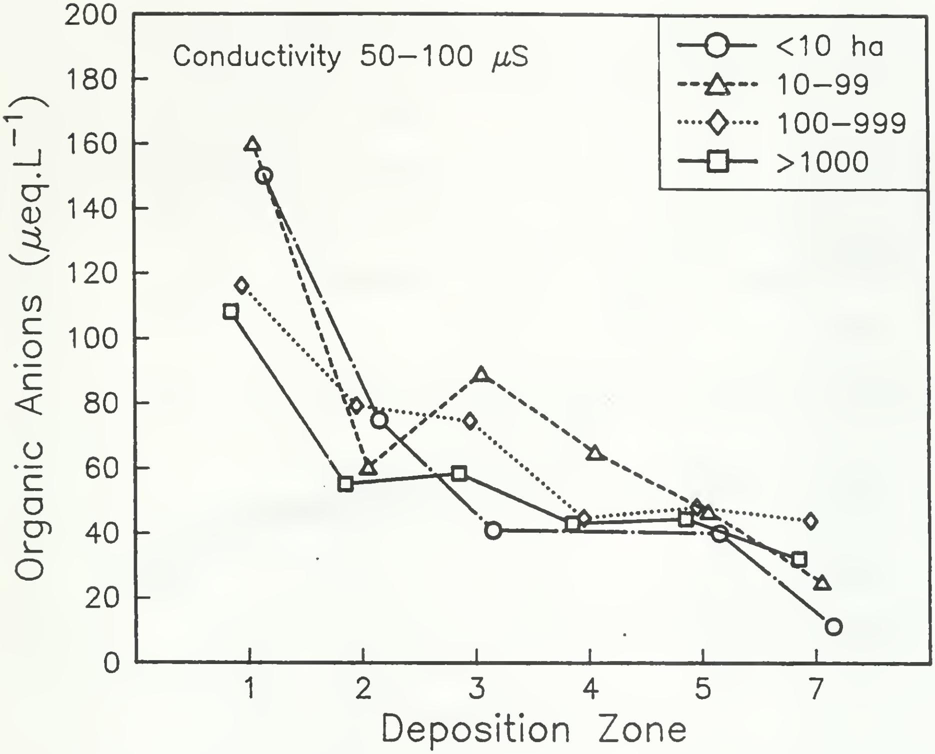

Figure 7.35: Relationship between S deposition (expressed at S deposition zone number) and mean organic anions for lakes with conductivity 50-100 μS by lake size class.

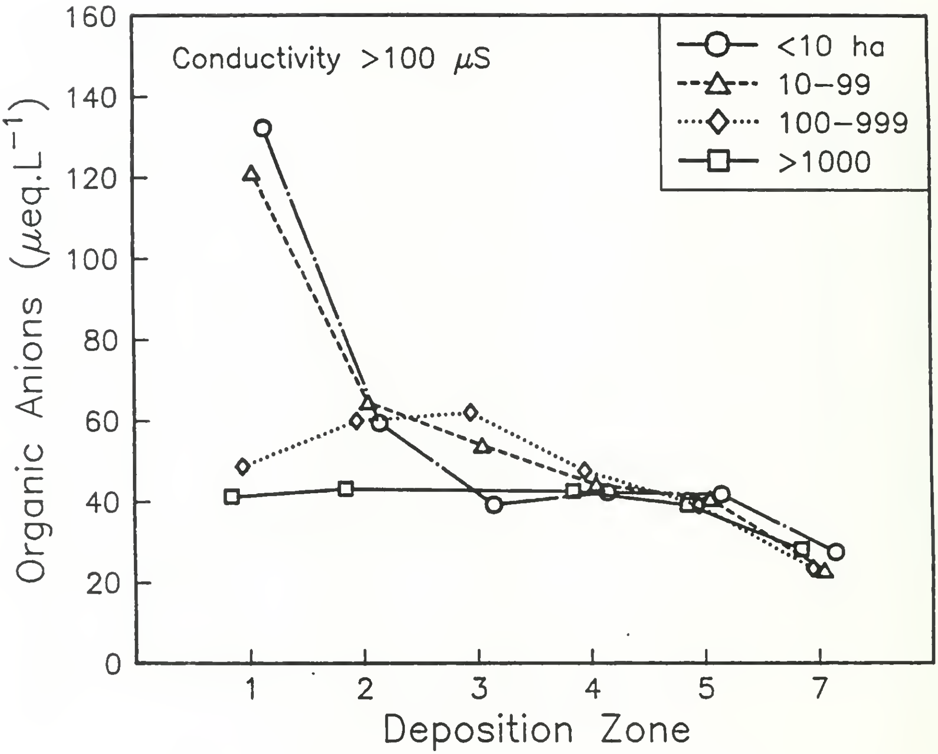

Figure 7.36: Relationship between S deposition (expressed at S deposition zone number) and mean organic anions for lakes with conductivity > 100 μS by lake size class.

8. Estimates of Lake Resources Affected by Acid Deposition

The data described in this report may be used to make estimates of the total number of lakes affected by acid deposition. The first level of estimate may be made at the deposition zone level. In this exercise, the pH and alkalinity distributions of sampled lakes within each size stratum and deposition zone were assumed to be representative of the total population of lakes within the zone. Most of the known biases in sampling the lakes were associated with lake size. As discussed in Section 7 and shown in Table 2.3, much of the sampling was of lakes greater than 10 ha in size, and in many cases, of lakes greater than 100 ha in size.

The variance of the estimates was calculated using the equation 8.1 (Cochran, 1977) :

$$V(\hat{N}) = [N_T(N_T - n_s)/(N_T - 1)][n_x/n_s][(n_s - n_x)/n_s] \qquad \text{(Equ. 8.1)}$$

where $\hat{N}$ = the estimated number of lakes lower than a particular value

N_T = the total number of lakes in the subpopulation (watershed or deposition zone)

n_x = the number of sampled lakes with value less than x.

and n_s = the number of lakes sampled in the subpopulation.

The standard error (se) of estimate was the square root of the variance.

8.1 Critical pH and Alkalinity Levels at the Deposition Zone Level

Estimates were made of numbers of lakes with pH and alkalinity below several specific levels. A pH of 6.0 was selected as the threshold where noticeable biological damage occurs. Pronounced biological effects were observed in experimentally-acidified Lake 223 (ELA) (Schindler et al. 1987) and in Plastic Lake, Ontario (Mierle et al. 1987) at pH's just below 6.0. In a review of fish species richness in 2931 Ontario lakes, Matuszek and Beggs (1988) found that after adjusting for lake size, lakes with pH <6.0 had fewer species than would be expected.

A pH of 6.0 corresponds to an alkalinity of approximately 40 μeq L^{-1} (Figure 5.4, and Dillon, unpublished studies). While an alkalinity of 20 ueq.L^{-1} (very approximately equivalent to a pH of 5.6) is indicative of lakes with significant biological damage, an alkalinity of 0 (very approximately equivalent to a pH of 5.2) indicates severe damage.

The results of these estimations at the deposition zone level are presented in Tables 8.1 through 8.6 for lakes in the 1-9.9, 10-99, and 100-999 ha size ranges. Extrapolations were not performed unless there were data for at least a 1% subsample of the total number of lakes within the size range.

These estimates should be viewed with some caution. One of the assumptions behind the stratification is that there is an unbiased subsample of lakes within the deposition zone strata. The most obvious source of bias in this data base is an orientation toward large lakes. By making separate estimates for each of the size ranges, some of this bias can be overcome. However, there may be other sources of bias within some deposition zones which are not accounted for, e.g. the influence of geology. For example, large portions of deposition zones 1 and 2 lie within the James and Hudson Bay lowlands, an area dominated by organic deposits. There are no lakes in our subsample from that portion of the region, although the number of lakes that they contain is relatively small. Additionally, zones 2 and 3 both contain portions of extensive clay deposits. It is not known whether the lakes in our data base proportionally represent these areas. On the other hand, our best estimates are those made for zones 4, 5 and 7 which are also those receiving the highest level of acid deposition. As a result, our estimates of the number of lakes affected are probably fairly reliable.

Our best estimate of lakes whose biota have been affected by acid deposition is approximately 19,000, the average of the number of lakes with pH < 6.0 (19,293) and the number with alkalinity < 40 μeq L^{-1} (18,408). These figures do not include estimates for small lakes in zones 1-3 or medium lakes in zone 1, so must be considered lower limits.

The number with significant biological damage is estimated as about 12,000, while those with severe damage (pH < 5.0) is about 5,500. Again, zones 1-3 are under-represented in these calculations, but it is expected that there will not be a large number

of lakes in these regions (with the possible exception of zone 3) that have extensive biological damage.

Exclusion of zone 7 from the calculations results in an estimate of 11,400 lakes biologically damaged by acid deposition.

Table 8.1: Estimates of numbers of small lakes (1-9.9 ha) with pH less than 5.0, 5.5 and 6.0 by deposition zone. Definitions as on p. 135.

Zone	N_T	n_s	$n_{<5.0}$	$\hat{N}_{<5.0}$	se	$n_{<5.5}$	$\hat{N}_{<5.5}$	se	$n_{<6.0}$	$\hat{N}_{<6.0}$	se
1	84024	7	0	*	*	0	*	*	1	*	*
2	40605	134	0	*	*	7	*	*	14	*	*
3	12862	87	0	*	*	4	*	*	11	*	*
4	11725	135	7	608	24	30	2606	45	54	4690	53
5	12672	470	10	270	16	49	1321	34	163	4395	53
6	1072	0	0	*	*	0	*	*	0	*	*
7	7708	87	38	3367	43	52	4607	43	65	5759	38
Sum	170668	920	55	4245	52	142	8534	71	308	14844	65

Table 8.2: Estimates of numbers of medium-sized lakes (10-99 ha) with pH less than 5.0, 5.5 and 6.0 by deposition zone. Definitions as on p. 135.

Zone	N_T	n_s	$n_{<5.0}$	$\hat{N}_{<5.0}$	se	$n_{<5.5}$	$\hat{N}_{<5.5}$	se	$n_{<6.0}$	$\hat{N}_{<6.0}$	se
1	48703	49	0	*	*	0	*	*	0	*	*
2	17992	439	0	0	0	2	82	9	19	779	27
3	4155	261	0	0	0	3	48	7	9	143	11
4	3423	353	7	68	8	30	291	15	76	737	23
5	4353	1402	15	47	6	88	273	13	346	1074	23
6	206	0	0	*	*	0	*	*	0	*	*
7	2594	282	66	607	20	102	938	23	160	1472	24
Sum	81426	2568	88	722	22	225	1632	33	638	4205	50

Table 8.3: Estimates of numbers of large lakes (100-999 ha) with pH less than 5.0, 5.5 and 6.0 by deposition zone. Definitions as on p. 135.

Zone	N_T	n_s	$n_{<5.0}$	$\hat{N}_{<5.0}$	se	$n_{<5.5}$	$\hat{N}_{<5.5}$	se	$n_{<6.0}$	$\hat{N}_{<6.0}$	se
1	5663	128	0	0	0	0	0	0	0	0	0
2	2507	523	0	0	0	1	5	4	5	24	4
3	383	152	0	0	0	0	0	0	0	0	0
4	253	149	1	2	1	4	7	3	13	22	3
5	704	508	1	1	1	12	17	5	63	87	5
6	33	0	0	*	*	0	*	*	0	*	*
7	304	165	18	33	14	35	64	23	60	111	6
Sum	9847	1611	20	36	4	52	93	6	141	244	9

Table 8.4: Estimates of number of small lakes (1-9.9 ha) with alkalinity less than 0, 20 and 40 μeq L^{-1} by deposition zone. Definitions as on p. 135.

Zone	N_T	n_s	$n_{<5.0}$	$\hat{N}_{<5.0}$	se	$n_{<5.5}$	$\hat{N}_{<5.5}$	se	$n_{<6.0}$	$\hat{N}_{<6.0}$	se
1	84024	7	0	*	*	0	*	*	0	*	*
2	40605	134	0	*	*	2	*	*	10	*	*
3	12862	87	1	*	*	9	*	*	14	*	*
4	11725	135	18	1563	37	40	3474	49	50	4343	52
5	12672	470	15	404	19	67	1806	39	138	3721	50
6	1072	0	0	*	*	0	*	*	0	*	*
7	7708	87	47	4164	44	62	5493	40	67	5936	37
Sum	170668	920	81	6131	61	180	10773	74	279	14000	81

Table 8.5: Estimates of number of medium lakes (10-99 ha) with alkalinity less than 0, 20 and 40 μeq L^{-1} by deposition zone. Definitions as on p. 135.

Zone	N_T	n_s	$n_{<5.0}$	$\hat{N}_{<5.0}$	se	$n_{<5.5}$	$\hat{N}_{<5.5}$	se	$n_{<6.0}$	$\hat{N}_{<6.0}$	se
1	48703	49	0	*	*	0	*	*	0	*	*
2	17992	439	0	0	0	6	246	15	17	697	26
3	4155	261	1	16	4	6	96	9	7	111	10
4	3423	353	16	155	12	48	465	19	86	834	24
5	4353	1402	29	90	8	163	506	17	296	919	22
6	206	0	0	*	*	0	*	*	0	*	*
7	2594	282	89	819	22	142	1306	24	166	1527	24
Sum	81426	2568	135	1080	27	365	2619	40	572	4088	49

Table 8.6: Estimates of number of large lakes (100-999 ha) with alkalinity less than 0, 20 and 40 μeq L^{-1} by deposition zone. Definitions as on p. 135.

Zone	N_T	n_s	$n_{<5.0}$	$\hat{N}_{<5.0}$	se	$n_{<5.5}$	$\hat{N}_{<5.5}$	se	$n_{<6.0}$	$\hat{N}_{<6.0}$	se
1	5663	128	0	0	0	0	0	0	0	0	0
2	2507	523	0	0	0	2	10	3	5	24	4
3	383	152	0	0	0	0	0	0	0	0	0
4	253	149	4	7	2	14	24	3	20	34	3
5	704	508	4	6	1	39	54	4	88	122	5
6	33	0	0	*	*	0	*	*	0	*	*
7	304	165	29	53	4	61	112	6	76	140	6
Sum	9847	1611	37	66	5	116	200	8	189	320	10

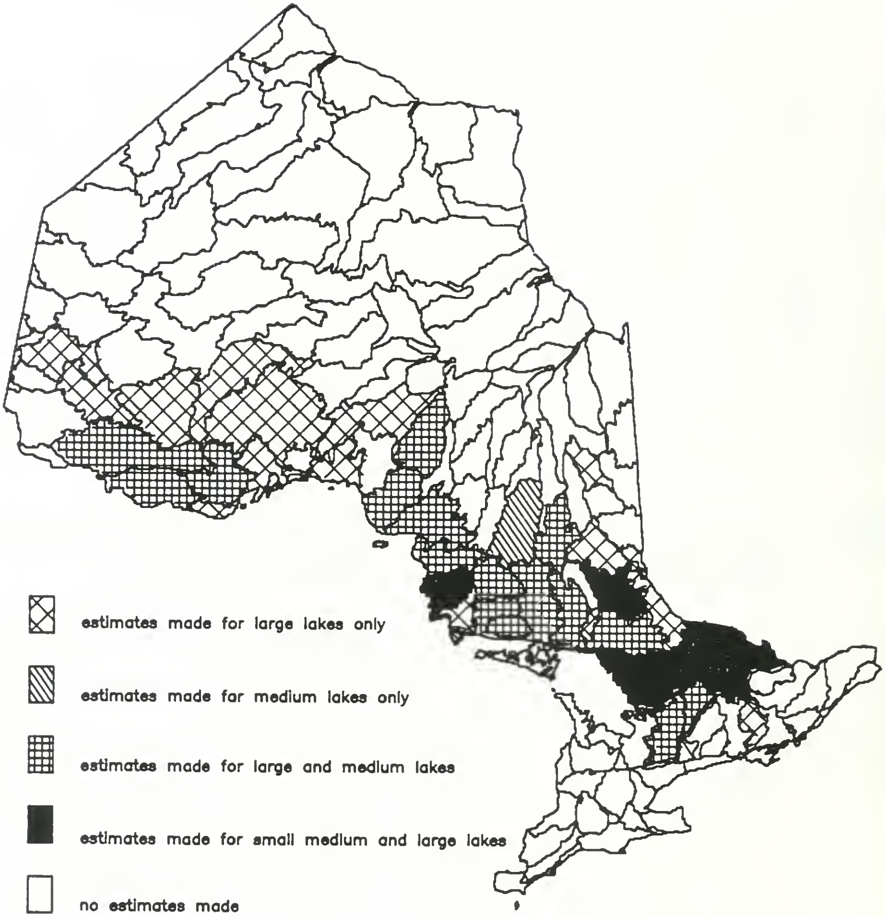

Figure 8.1: Map showing areas of estimates by lake size.

8.2: Estimation of Critical pH and Alkalinity Levels for Well Sampled Watersheds

An approach which gives much more accurate estimates can be done for a small subsample of lakes in Ontario. In this exercise, minimum sampling criteria were established on a watershed basis. These criteria were a minimum of 30 lakes within the size range and a minimum of a 2% subsample within that range. In many cases, this was inappropriate for the 100-999 ha size range, where there were less than 30 lakes in the watershed. In this size range only, extrapolations were made if 50% or more of the lakes had been sampled. Extrapolations were then made for each of the watersheds which met the criteria, and the separate estimates were aggregated. The only assumption behind this approach is that within each watershed, the lakes within a given size range were a representative subsample. Variation and sampling bias on an individual tertiary watershed are felt to be much smaller than the bias at the deposition zone level. The results of this extrapolation for three lake pH levels are presented in Table 8.7. The results of extrapolation for three alkalinity concentrations are given in Table 8.8.

Table 8.7: Estimates of lake acidification estimated by pH for well sampled watersheds. Definitions as on p. 135.

Size Range 1-9.9 ha

Size Range	Number of Watersheds	N_T	n_s	$n_{<5.0}$	$\hat{N}_{<5.0}$	se	$n_{<5.5}$	$\hat{N}_{<5.5}$	se	$n_{<6.0}$	$\hat{N}_{<6.0}$	se
1-9.9	8	9936	563	27	668	48	83	1854	88	216	4070	116
10-99	26	15125	2426	81	549	53	222	1239	101	597	2962	170
100-99	38	3350	1582	20	31	6	52	76	14	143	200	22
Totals	39	28411	4571	128	1248	107	357	3169	203	956	7232	308

Table 8.8: Estimates of lake acidification estimated by alkalinity for well sampled watersheds. Definitions as on p. 135.

Size Range 1-9.9 ha

Size Range	Number of Watersheds	N_T	n_s	$n_{<0}$	$\hat{N}_{<0}$	se	$n_{<20}$	$\hat{N}_{<20}$	se	$n_{<40}$	$\hat{N}_{<40}$	se
1-9.9	8	9936	563	39	1006	28	123	2699	38	199	4051	44
10-99	26	15125	2426	132	909	24	362	1947	31	659	3196	39
100-999	38	3350	1582	42	63	4	119	167	6	198	293	8
Totals	39	28411	4571	213	1978	37	604	4813	49	1056	7540	59

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Appendix A: Number of Lakes Sampled by Watershed

		Number of Lakes*	Lakes Sampled	% Sampled
2A	**Western Lake Superior Tributaries**			
2AA	Eight Superior Tributaries	274	20	7.30
2AB	Five Superior Tributaries	1875	83	4.43
2AC	Twenty-three Superior Tributaries	1243	62	4.99
2AD	Nipigon River	5276	66	1.25
2AE	Twenty-two Superior Tributaries	1084	24	2.21
2B	**Eastern Lake Superior Tributaries**			
2BA	Twenty Superior Tributaries	2450	45	1.84
2BB	Pic River and Two Other Superior Tributaries	1910	37	1.94
2BC	Thirty Superior Tributaries	3163	131	4.14
2BD	Thirty-one Superior Tributaries	4900	198	4.04
2BE	Twenty-one Superior Tributaries	3073	145	4.72
2BF	Twenty-two Superior Tributaries	2726	226	8.29
2C	**North Channel Tributaries and Manitoulin Island**			
2CA	Fourteen St. Marys R.- North Channel Tributaries	1245	65	5.22
2CB	Upper Mississagi River	2943	48	1.63
2CC	Lower Mississagi River	1891	103	5.45
2CD	Four North Channel Tributaries	1008	100	9.92
2CE	Spanish River and One North Channel Tributary	4271	108	2.53
2CF	Seven North Channel Tribs. and Trib. to Spanish R.	2846	189	6.64
2CG	Manitoulin Island	305	1	0.33
2D	**French River and Islands**			
2DA	Upper Wanapitei River	1209	39	3.23
2DB	Lower Wanapitei River	207	15	7.25
2DC	Sturgeon River	2622	209	7.97
2DD	French River and Pickerel River	1289	90	6.98
2E	**Eastern Georgian Bay Tributaries**			
2EA	Nineteen Georgian Bay Tributaries	1441	308	21.37
2EB	Moon River and Go Home River	1809	479	26.48
2EC	Severn River	937	123	13.13
2ED	Nottawasaga River and Thirteen Other Tributaries	157	0	0.00

(cont'd)

Appendix A: (Cont'd)

		Number of Lakes*	Lakes Sampled	% Sampled
2F	**Western Georgian Bay and Eastern Lake Huron Tributaries**			
2FA	Bruce Peninsula Streams	119	0	0.00
2FB	Fourteen Georgian Bay Tributaries	31	0	0.00
2H	**Lake Ontario Tributaries**			
2FC	Saugeen River	136	0	0.00
2FD	Twenty-three Lake Huron Tributaries	16	0	0.00
2FE	Maitland River and Two Other Tributaries	21	0	0.00
2FF	Eighteen Lake Huron Tributaries	13	0	0.00
2G	**Tributaries of the St. Clair River and Lake Erie**			
2GA	Upper Grand River	117	0	0.00
2GB	Lower Grand River	74	0	0.00
2GC	Fifteen Lake Eire Tributaries	140	0	0.00
2GD	Upper Thames River	64	0	0.00
2GE	Lower Thames River	20	0	0.00
2GF	Nine Lake Eire Tributaries	2	0	0.00
2GG	St. Clair River and Lake St. Clair Tributaries	79	0	0.00
2GH	Essex County	52	0	0.00
2HA	Niagra River - Western Lake Ontario Tributaries	67	0	0.00
2HB	Lake Ontario Tributaries	128	0	0.00
2HC	Lake Ontario Tributaries	187	0	0.00
2HD	Lake Ontario Tributaries	37	0	0.00
2HE	Prince Edward County	22	0	0.00
2HF	Cameron Lake Drainage	945	175	18.52
2HG	Scugog River	35	0	0.00
2HH	Kawartha Lakes Drainage	747	36	4.82
2HJ	Otonabee River - Rice Lake	52	0	0.00
2HK	Trent River and Crowe River	452	23	5.09
2HL	Moira River	369	7	1.90
2HM	Lake Ontario Tributaries	253	8	3.16
2J	**Northern Ottawa River**			
2JC	Blanche River	551	17	3.09
2JD	Montreal River	2592	109	4.21
2JE	Lake Temiskaming - Ottawa River	1996	163	8.17

(cont'd)

		Number of Lakes*	Lakes Sampled	% Sampled
2K	**Central Ottawa River**			
2KA	Holden Lake - Ottawa River	401	132	32.92
2KB	Petawawa River	1998	224	11.21
2KC	Allumette Lake - Lac Des Chats - Ottawa River	693	127	18.33
2KD	Upper Madawaska River	1782	466	26.15
2KE	Lower Madawaska River	516	24	4.65
2KF	Mississipi River - Lac Deschenes	658	10	1.52
2L	**Lower Ottawa River**			
2LA	Rideau River	173	12	6.94
2LB	Lower Ottawa River	33	0	0.00
2M	**Western St. Lawrence River**			
2MA	Western St. Lawrence Tributaries	225	15	6.67
2MB	West St. Lawrence River	41	0	0.00
2MC	Lake St. Lawrence - Lake St. Frances	14	0	0.00
4A	**Hayes River**			
4AC	Upper Gods River	941	0	0.00
4AD	Lower Gods River	1602	0	0.00
4AE	Echoing River	2669	0	0.00
4B	**Hudson Bay Tributaries Between Nelson and Severn Rivers**			
4BA	Twelve Hudson Bay Tributaries	4129	0	0.00
4BB	Five Hudson Bay Tributaries	887	0	0.00
4C	**Severn River**			
4CA	Upper Severn River	8035	22	0.27
4CB	Windigo River - Shade River	3812	15	0.39
4CC	Lower Severn River	4383	0	0.00
4CD	Sachigo River	5343	0	0.00
4CE	Fawn River	4226	0	0.00
4CF	Beaver River	1864	0	0.00

(cont'd)

Appendix A: (Cont'd)

		Number of Lakes*	Lakes Sampled	% Sampled
4D	**Winisk River and Hudson Bay Tributaries between Severn and Winisk Rivers**			
4DA	Upper Winisk River	9133	11	0.12
4DB	Middle Winisk River	10213	1	0.01
4DC	Lower Winisk River	9435	0	0.00
4DD	Twenty-four Hudson Bay Tributaries	7062	0	0.00
4E	**Hudson and James Bays Tributaries between Winisk and Attawapiskat Rivers**			
4EA	Upper Ekwan River	3578	0	0.00
4EB	Lower Ekwan River	390	0	0.00
4EC	Five Hudson Bay Tribs. - 13 James Bay Tributaries	5117	0	0.00
4ED	Sixteen Hudson Bay Tributaries	7201	0	0.00
4F	**Attawapiskat River**			
4FA	Upper Attawapiskat River	4761	12	0.25
4FB	Middle Attawapiskat River	2811	5	0.18
4FC	Lower Attawapiskat River	5351	0	0.00
4G	**Upper Albany River**			
4GA	Upper Albany River	8108	31	0.38
4GB	Ogoki Diversion	5290	65	1.23
4GC	West Middle Albany River	3934	5	0.13
4GD	Middle Albany River	2720	5	0.18
4GE	Ogoki River	1055	1	0.09
4GF	East Middle Albany River	573	2	0.35
4H	**Lower Albany River and James Bay Tributaries between Attawapiskat Rivers and Moose Rivers**			
4HA	Lower Albany River	5215	0	0.00
4HB	Ten James Bay Tributaries	2782	0	0.00
4HC	Upper Kapiskau River	273	0	0.00
4HD	Kapiskau R. and Six Other James Bay Tributaries	3923	0	0.00

(cont'd)

Appendix A: (Cont'd)

		Number of Lakes*	Lakes Sampled	% Sampled
4J	**Upper Missinaibi River**			
4JA	Upper Kabinakagami River	1024	18	1.76
4JB	Lower Kabinakagami River	422	33	7.82
4JC	Nagagami River	1984	123	6.20
4JD	Upper Kenogami River	2996	48	1.60
4JE	Drowning River	402	5	1.24
4JF	Little Current River	2360	13	0.55
4JG	Lower Kenogami River	108	0	0.00
4K	**Kwataboahegan River**			
4KA	Kwataboahegan River	865	0	0.00
4L	**Moose River**			
4LA	Upper Mattagami River	2311	141	6.10
4LB	Middle Mattagami River	74	23	31.08
4LC	Upper Groundhog River	3102	54	1.74
4LD	Lower Groundhog River	271	17	6.27
4LE	Upper Kapuskasing River	1234	34	2.76
4LF	Lower Kapuskasing River	396	24	6.06
4LG	Cheepash River	380	9	2.37
4LH	Upper Missinaibi River	1053	21	1.99
4LJ	South Middle Missinaibi River	357	4	1.12
4LK	North Middle Missinaibi River	638	17	2.66
4LL	Opasatika River	697	16	2.30
4LM	Lower Missinabi River	87	0	0.00
4M	**Abitibi and North French River**			
4MA	Upper Abitibi River	294	7	2.38
4MB	Black River	566	11	1.94
4MC	Middle Abitibi River	480	6	1.25
4MD	Fredrickhouse River	926	27	2.92
4ME	Lower Abitibi River	1490	14	0.94
4MF	French River	1713	4	0.23
4N	**Southern James Bay Tributaries**			
4NB	Upper River Turgeon	199	2	1.01
4NC	Seven James Bay Tributaries	2269	7	0.31

(cont'd)

Appendix A: (Cont'd)

		Number of Lakes[*]	Lakes Sampled	% Sampled
5P	**Winnipeg River**			
5PA	Upper Rainy River	3543	165	4.66
5PB	Middle Rainy River	5692	193	3.39
5PC	Lower Rainy River	30	1	3.33
5PD	Lake of the Woods and Drainage	1998	31	1.55
5PE	Upper Winnipeg River	955	21	2.20
5PF	Lower Winnipeg River	49	1	2.04
5PG	Whiteshell River	35	0	0.00
5PJ	Oiseau River	593	2	0.34
5Q	**English River**			
5QA	Upper English River	3559	53	1.49
5QB	Lac Seul Drainage	1763	30	1.70
5QC	Pakwash River	1307	9	0.69
5QD	Wabigoon River	2074	44	2.12
5QE	Lower English River	2412	32	1.33
5R	**Lake Winnipeg Tributaries**			
5RA	Ten Lake Winnipeg Tributaries	312	3	0.96
5RB	Four Lake Winnipeg Tributaries	1889	4	0.21
5RC	Upper Berens River	3610	16	0.44
5RD	Lower Berens River and Others	232	1	0.43
5RE	Poplar River and Others	456	0	0.00

[*] Estimated Number of Lakes Between 1 and 9999 ha

Appendix B: Lakes Sampled by Watershed and Lake Size

	----1-9.9 ha----			----10-99 ha-----			---100-999 ha---			--1000-9999 ha--		
Wshed	#	Samp	%	#	Samp	%	#	Samp	%	#	Samp	%
2AA	197	2	1.0	57	6	10.5	17	9	52.9	3	3	100.0
2AB	1247	15	1.2	554	33	6.0	68	27	39.7	6	8	133.3
2AC	886	7	0.8	314	29	9.2	42	24	57.1	1	2	200.0
2AD	3552	7	0.2	1501	12	0.8	202	34	16.8	21	13	61.9
2AE	884	11	1.2	180	9	5.0	20	4	20.0	0	0	-
2BA	1998	3	0.2	406	11	2.7	42	30	71.4	4	1	25.0
2BB	1340	1	0.1	522	14	2.7	46	21	45.7	2	1	50.0
2BC	2470	20	0.8	640	66	10.3	49	41	83.7	4	4	100.0
2BD	3695	30	0.8	1104	101	9.1	88	60	68.2	13	7	53.8
2BE	2434	28	1.2	608	90	14.8	31	27	87.1	0	0	-
2BF	2157	84	3.9	536	117	21.8	33	25	75.8	0	0	-
2CA	967	11	1.1	248	29	11.7	27	22	81.5	3	3	100.0
2CB	2107	3	0.1	784	20	2.6	48	22	45.8	4	3	75.0
2CC	1409	3	0.2	442	64	14.5	36	32	88.9	4	4	100.0
2CD	651	13	2.0	293	43	14.7	59	40	67.8	5	3	60.0
2CE	3136	9	0.3	1044	61	5.8	79	31	39.2	12	7	58.3
2CF	2063	32	1.6	670	96	14.3	108	55	50.9	5	6	120.0
2CG	194	0	0.0	82	0	0.0	26	0	0.0	3	1	33.3
2DA	931	8	0.9	255	20	7.8	21	10	47.6	2	1	50.0
2DB	146	1	0.7	53	9	17.0	8	5	62.5	0	0	-
2DC	1899	49	2.6	637	96	15.1	74	54	73.0	12	10	83.3
2DD	892	10	1.1	352	40	11.4	42	37	88.1	3	3	100.0
2EA	960	61	6.4	407	169	41.5	69	74	107.2	5	4	80.0
2EB	1169	92	7.9	556	302	54.3	77	78	101.3	7	7	100.0
2EC	716	15	2.1	193	81	42.0	22	22	100.0	6	5	83.3
2ED	110	0	0.0	40	0	0.0	7	0	0.0	0	0	-
2FA	59	0	0.0	43	0	0.0	17	0	0.0	0	0	-
2FB	17	0	0.0	13	0	0.0	1	0	0.0	0	0	-
2FC	102	0	0.0	34	0	0.0	0	0	-	0	0	-
2FD	13	0	0.0	3	0	0.0	0	0	-	0	0	-
2FE	15	0	0.0	6	0	0.0	0	0	-	0	0	-
2FF	12	0	0.0	0	0	-	1	0	0.0	0	0	-
2GA	101	0	0.0	12	0	0.0	3	0	0.0	1	0	0.0
2GB	62	0	0.0	12	0	0.0	0	0	-	0	0	-
2GC	121	0	0.0	19	0	0.0	0	0	-	0	0	-
2GD	56	0	0.0	5	0	0.0	3	0	0.0	0	0	-

(cont'd)

Appendix B: (Cont'd)

Wshed	----1-9.9 ha---- #	Samp	%	----10-99 ha----- #	Samp	%	---100-999 ha--- #	Samp	%	--1000-9999 ha-- #	Samp	%
2GE	18	0	0.0	2	0	0.0	0	0	-	0	0	-
2GF	2	0	0.0	0	0	-	0	0	-	0	0	-
2GG	70	0	0.0	8	0	0.0	1	0	0.0	0	0	-
2GH	38	0	0.0	13	0	0.0	1	0	0.0	0	0	-
2HA	55	0	0.0	10	0	0.0	2	0	0.0	0	0	-
2HB	118	0	0.0	7	0	0.0	3	0	0.0	0	0	-
2HC	174	0	0.0	13	0	0.0	0	0	-	0	0	-
2HD	35	0	0.0	2	0	0.0	0	0	-	0	0	-
2HE	13	0	0.0	3	0	0.0	4	0	0.0	2	0	0.0
2HF	630	13	2.1	257	108	42.0	53	51	96.2	5	3	60.0
2HG	33	0	0.0	1	0	0.0	0	0	-	1	0	0.0
2HH	548	4	0.7	169	19	11.2	22	11	50.0	8	2	25.0
2HJ	47	0	0.0	5	0	0.0	0	0	-	0	0	-
2HK	297	2	0.7	126	13	10.3	28	7	25.0	1	1	100.0
2HL	295	0	0.0	64	2	3.1	9	4	44.4	1	1	100.0
2HM	166	0	0.0	69	1	1.4	18	7	38.9	0	0	-
2JC	379	2	0.5	146	5	3.4	24	10	41.7	2	0	0.0
2JD	1848	16	0.9	669	46	6.9	67	42	62.7	8	5	62.5
2JE	1422	15	1.1	511	104	20.4	55	38	69.1	8	6	75.0
2KA	273	51	18.7	117	73	62.4	9	8	88.9	2	0	0.0
2KB	1623	35	2.2	322	142	44.1	48	43	89.6	5	4	80.0
2KC	544	39	7.2	127	74	58.3	13	8	61.5	9	6	66.7
2KD	1311	152	11.6	402	247	61.4	63	59	93.7	6	8	133.3
2KE	400	13	3.3	101	8	7.9	12	1	8.3	3	2	66.7
2KF	468	0	0.0	153	2	1.3	32	5	15.6	5	3	60.0
2LA	95	0	0.0	56	3	5.4	19	6	31.6	3	3	100.0
2LB	27	0	0.0	5	0	0.0	0	0	-	1	0	0.0
2MA	94	0	0.0	86	2	2.3	41	10	24.4	4	3	75.0
2MB	39	0	0.0	2	0	0.0	0	0	-	0	0	-
2MC	10	0	0.0	3	0	0.0	1	0	0.0	0	0	-
4AC	277	0	0.0	567	0	0.0	92	0	0.0	5	0	0.0
4AD	940	0	0.0	605	0	0.0	52	0	0.0	5	0	0.0
4AE	1754	0	0.0	859	0	0.0	52	0	0.0	4	0	0.0
4BA	2904	0	0.0	1205	0	0.0	20	0	0.0	0	0	-
4BB	384	0	0.0	478	0	0.0	25	0	0.0	0	0	-

(cont'd)

Appendix B: (Cont'd)

	----1-9.9 ha----			----10-99 ha-----			---100-999 ha---			--1000-9999 ha--		
Wshed	#	Samp	%	#	Samp	%	#	Samp	%	#	Samp	%
4CA	5344	0	0.0	2398	9	0.4	261	8	3.1	32	5	15.6
4CB	1600	0	0.0	1833	2	0.1	356	10	2.8	23	3	13.0
4CC	2322	0	0.0	1792	0	0.0	264	0	0.0	5	0	0.0
4CD	2675	0	0.0	2332	0	0.0	328	0	0.0	8	0	0.0
4CE	2236	0	0.0	1744	0	0.0	237	0	0.0	9	0	0.0
4CF	1210	0	0.0	637	0	0.0	17	0	0.0	0	0	-
4DA	5246	0	0.0	3369	5	0.1	487	5	1.0	31	1	3.2
4DB	5610	0	0.0	3998	0	0.0	589	1	0.2	16	0	0.0
4DC	6176	0	0.0	2999	0	0.0	258	0	0.0	2	0	0.0
4DD	4828	0	0.0	2123	0	0.0	108	0	0.0	3	0	0.0
4EA	1950	0	0.0	1429	0	0.0	193	0	0.0	6	0	0.0
4EB	179	0	0.0	197	0	0.0	13	0	0.0	1	0	0.0
4EC	3482	0	0.0	1521	0	0.0	109	0	0.0	5	0	0.0
4ED	5026	0	0.0	2079	0	0.0	94	0	0.0	2	0	0.0
4FA	2705	1	0.0	1729	8	0.5	299	3	1.0	28	0	0.0
4FB	1533	0	0.0	1096	0	0.0	173	3	1.7	9	2	22.2
4FC	3652	0	0.0	1548	0	0.0	143	0	0.0	8	0	0.0
4GA	5384	3	0.1	2391	10	0.4	297	13	4.4	36	5	13.9
4GB	3285	1	0.0	1739	16	0.9	239	40	16.7	27	8	29.6
4GC	2688	0	0.0	1079	1	0.1	151	3	2.0	16	1	6.3
4GD	1636	0	0.0	941	0	0.0	133	4	3.0	10	1	10.0
4GE	677	0	0.0	322	0	0.0	51	1	2.0	5	0	0.0
4GF	288	0	0.0	243	0	0.0	37	1	2.7	5	1	20.0
4HA	3805	0	0.0	1328	0	0.0	75	0	0.0	7	0	0.0
4HB	2061	0	0.0	714	0	0.0	7	0	0.0	0	0	-
4HC	91	0	0.0	163	0	0.0	19	0	0.0	0	0	-
4HD	2916	0	0.0	983	0	0.0	24	0	0.0	0	0	-
4JA	662	1	0.2	342	11	3.2	16	4	25.0	4	2	50.0
4JB	326	22	6.7	87	8	9.2	7	3	42.9	2	0	0.0
4JC	1447	26	1.8	479	60	12.5	53	33	62.3	5	4	80.0
4JD	2215	1	0.0	696	17	2.4	76	25	32.9	9	5	55.6
4JE	276	0	0.0	111	1	0.9	12	3	25.0	3	1	33.3
4JF	1685	0	0.0	579	2	0.3	84	8	9.5	12	3	25.0
4JG	78	0	0.0	23	0	0.0	6	0	0.0	1	0	0.0
4KA	576	0	0.0	280	0	0.0	9	0	0.0	0	0	-

(cont'd)

Appendix B: (Cont'd)

Wshed	----1-9.9 ha---- #	Samp	%	----10-99 ha----- #	Samp	%	---100-999 ha--- #	Samp	%	--1000-9999 ha-- #	Samp	%
4LA	1622	20	1.2	612	65	10.6	72	52	72.2	5	4	80.0
4LB	509	1	0.2	191	16	8.4	14	6	42.9	0	0	-
4LC	2225	8	0.4	792	30	3.8	80	13	16.3	5	3	60.0
4LD	178	1	0.6	86	15	17.4	7	1	14.3	0	0	-
4LE	907	10	1.1	289	17	5.9	33	3	9.1	5	4	80.0
4LF	277	3	1.1	104	17	16.3	13	3	23.1	2	1	50.0
4LG	339	3	0.9	38	5	13.2	1	1	100.0	2	0	0.0
4LH	788	11	1.4	241	5	2.1	22	4	18.2	2	1	50.0
4LJ	252	0	0.0	89	3	3.4	15	0	0.0	1	1	100.0
4LK	496	0	0.0	125	12	9.6	14	3	21.4	3	2	66.7
4LL	547	1	0.2	130	6	4.6	19	9	47.4	1	0	0.0
4MA	220	0	0.0	66	4	6.1	8	3	37.5	0	0	-
4MB	406	1	0.2	146	5	3.4	13	4	30.8	1	1	100.0
4MC	351	0	0.0	123	2	1.6	6	4	66.7	0	0	-
4MD	701	14	2.0	210	6	2.9	13	6	46.2	2	1	50.0
4ME	1081	3	0.3	365	1	0.3	40	9	22.5	4	1	25.0
4MF	1083	0	0.0	570	0	0.0	56	4	7.1	4	0	0.0
4NB	20	0	0.0	156	0	0.0	23	2	8.7	0	0	-
4NC	1433	1	0.1	736	1	0.1	96	4	4.2	4	1	25.0
5PA	2371	12	0.5	958	51	5.3	192	80	41.7	22	22	100.0
5PB	3479	31	0.9	1843	67	3.6	323	72	22.3	47	23	48.9
5PC	22	0	0.0	8	1	12.5	0	0	-	0	0	-
5PD	1149	2	0.2	723	1	0.1	115	27	23.5	11	1	9.1
5PE	493	0	0.0	380	6	1.6	71	10	14.1	11	5	45.5
5PF	26	0	0.0	21	0	0.0	1	1	100.0	1	0	0.0
5PG	14	0	0.0	16	0	0.0	5	0	0.0	0	0	-
5PJ	363	0	0.0	193	0	0.0	35	1	2.9	2	1	50.0
5QA	1997	2	0.1	1279	10	0.8	248	25	10.1	35	16	45.7
5QB	830	3	0.4	756	10	1.3	159	11	6.9	18	6	33.3
5QC	614	0	0.0	571	3	0.5	107	4	3.7	15	2	13.3
5QD	1194	1	0.1	736	9	1.2	126	24	19.0	18	10	55.6
5QE	1375	0	0.0	840	1	0.1	167	19	11.4	30	12	40.0
5RA	163	0	0.0	133	0	0.0	15	3	20.0	1	0	0.0
5RB	1004	0	0.0	781	0	0.0	90	3	3.3	14	1	7.1
5RC	1684	0	0.0	1665	2	0.1	240	12	5.0	21	2	9.5
5RD	101	0	0.0	115	0	0.0	16	1	6.3	0	0	-
5RE	218	0	0.0	208	0	0.0	29	0	0.0	1	0	0.0

Appendix C: Summary of analytical procedures for water chemistry parameters

(Ontario Ministry of the Environment (1) and Environment Canada, Water Quality Branch (2).) There are four Ontario Ministry of the Environment laboratories involved: Rexdale, Dorset, Thunder Bay, and Kingston.

Parameter	Analytical Procedure
pH	Combination glass and reference electrode pH meter.
Alkalinity	Potentiometrically determined end point using Gran analysis of titration data.
Conductivity	Conductivity meter, temperature corrected.
Colour	Apparent Colour - Comparator disc technique, includes dissolved and suspended substances. True Colour - Colourimetric measurement after correction for residual turbidity.
Dissolved Organic Carbon	Colourimetric measurement after removal of inorganic carbon species.
Calcium	Atomic absorption spectrophotometry.
Magnesium	Atomic absorption spectrophotometry.
Sodium	Atomic absorption spectrophotometry. (1) Automated flame photometry. (2)
Potassium	Atomic absorption spectrophotometry. (1) Automated flame photometry. (2)

(cont'd)

Appendix C: (Cont'd)

Parameter	Analytical Procedure
Sulphate	Methyl-thymol blue (MTB) colourimetric method. (2) Before June 1980, methyl-thymol blue (MTB) colourimetric method. After June 1980, automated suppressed ion chromatography. (1)
Aluminum	Graphite furnace atomic absorption spectrophotometry.
Manganese	Atomic absorption spectrophotometry. (2) Before June 1985, manganese-formaldoxime colourimetric determination. After June 1985, atomic absorption spectrophotometry after preconcentration. (1)
Iron	Atomic absorption spectrophotometry. (2) Before June 1985, digestion and analysis colourimetrically by TPTZ method. After June 1985, atomic absorption spectrophotometry after preconcentration. (1)
Chloride	Mercuric thiocyanate colourimetry. (2) Before June 1980, mercuric thiocyanate colourimetry. After June 1980, automated suppressed ion chromatography. (1)
Nitrate + Nitrite	Hydrazine reduction method, automated deazotization colourimetry. (1)

Appendix D: Watersheds included in each Deposition Zone

Zone	Wshed	1000-9999 ha		100-999 ha		10-99 ha		1-9.9 ha	
		N	Area	N	Area	N	Area	N	Area
1	4AD**	5	22909	52	13891	605	14346	940	3739
1	4AE**	4	14253	52	10279	859	18990	1754	7792
1	4BA**	-	-	20	3136	1205	23269	2904	12480
1	4BB**	-	-	25	5848	478	10785	384	1797
1	4CA**	32	78698	261	71247	2398	59600	5344	20910
1	4CB**	23	72068	356	75332	1833	54563	1600	9411
1	4CC**	5	15742	264	55826	1792	45416	2322	11734
1	4CD**	8	23917	328	57506	2332	64659	2675	16143
1	4CE**	9	16288	237	45143	1744	47621	2236	12165
1	4CF**	-	-	17	3288	637	11928	1210	5242
1	4DA**	31	83470	487	115021	3369	87007	5246	23289
1	4DB**	16	43747	589	130228	3998	112513	5610	26974
1	4DC**	2	3642	258	57728	2999	71174	6176	27113
1	4DD**	3	5504	108	22642	2123	42057	4828	21015
1	4EA**	6	11344	193	36003	1429	37292	1950	10520
1	4EB**	1	2428	13	3581	197	4634	179	616
1	4EC**	5	13207	109	22652	1521	34807	3482	15283
1	4ED**	2	5200	94	19941	2079	44101	5026	21616
1	4FA**	28	50563	299	75284	1729	44323	2705	11035
1	4FB**	9	28813	173	39072	1096	31798	1533	7127
1	4FC**	8	22662	143	33639	1548	34064	3652	15401
1	4GA01	5	8861	34	9075	307	7001	924	4039
1	4GA02	3	15338	30	5999	294	6404	301	1316
1	4GA03	-	-	4	971	35	658	74	324
1	4GA04	1	1012	10	2023	51	1194	84	367
1	4GA05	-	-	2	223	29	870	44	194
1	4GA06	1	1093	7	1840	74	1599	104	453
1	4GA07	5	17235	28	6111	200	3885	327	1429
1	4GA08	-	-	3	1335	22	658	39	173
1	4GA09	-	-	8	1831	13	273	52	226
1	4GA10	4	17240	25	5682	223	5311	409	1790
1	4GA11	-	-	21	4391	110	2792	143	625
1	4GA12	3	9955	20	4452	172	3966	301	1316
1	4GA13	-	-	5	856	42	1032	123	539
1	4GC01	-	-	7	1892	28	506	56	244
1	4GC02	1	1735	18	3885	79	1831	243	1063
1	4GC03	2	4411	20	5109	111	2661	146	639
1	4GC04	4	12586	12	2469	77	1953	203	887
1	4GC05	1	5787	3	2469	46	911	82	359
1	4GC06	1	1312	5	324	23	617	42	183
1	4GC07	-	-	3	1366	16	445	25	108
1	4GD01	-	-	-	-	5	162	50	228

(cont'd)

Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha N	1000-9999 ha Area	100-999 ha N	100-999 ha Area	10-99 ha N	10-99 ha Area	1-9.9 ha N	1-9.9 ha Area
1	4GD02	-	-	1	243	7	202	43	194
1	4GD03	2	23512	13	2752	111	3369	331	1502
1	4GD04	-	-	-	-	1	30	20	90
1	4GD05	-	-	4	627	75	2428	158	714
1	4GD06	-	-	9	1538	65	2034	119	540
1	4GD07	-	-	2	243	17	546	37	169
1	4GD08	-	-	2	405	24	921	27	121
1	4GD15	3	8658	21	4219	89	2448	150	681
1	4GE01	-	-	-	-	2	69	8	23
1	4GE02	-	-	2	330	7	213	17	57
1	4GE03	1	1700	-	-	2	64	9	22
1	4GE04	-	-	6	1291	30	643	60	235
1	4GE05	-	-	4	963	5	105	8	38
1	4GE06	-	-	-	-	9	253	9	37
1	4GE11	-	-	3	1381	32	876	66	227
1	4GF**	5	15829	37	9462	243	6646	288	1064
1	4HA**	7	31525	75	18150	1328	28379	3805	15665
1	4HB**	-	-	7	1649	714	10927	2061	8451
1	4HC**	-	-	19	3804	163	3966	91	465
1	4HD**	-	-	24	5099	983	15904	2916	12102
1	4JE01	3	4780	9	2346	92	3099	206	836
1	4JE02	-	-	-	-	5	214	12	34
1	4JF01	1	1221	1	113	12	293	16	62
1	4JF02	-	-	3	934	9	282	8	57
1	4JF03	-	-	1	254	8	138	5	25
1	4JF04	-	-	-	-	4	99	-	0
1	4JF14	1	4293	1	625	37	987	92	333
1	4JF15	2	2863	7	1752	30	836	69	222
1	4JG**	1	3116	6	1740	23	654	78	236
1	5PD01	-	-	21	4694	148	4372	176	746
1	5PD07	2	8400	25	7362	171	5059	179	863
1	5PD08	1	2478	7	2988	74	2001	93	481
1	5PD09	-	-	1	649	1	51	2	10
1	5PD10	-	-	-	-	1	40	2	5
1	5PD11	-	-	-	-	9	159	10	53
1	5PD12	-	-	-	-	-	-	1	3
1	5PE**	11	25214	71	17325	380	11879	493	2260
1	5PF**	1	1934	1	196	21	698	26	126
1	5PG**	-	-	5	798	16	509	14	76
1	5PJ**	2	2809	35	7465	193	5902	363	1635
1	5QB04	1	1514	9	1681	54	1477	81	316
1	5QB05	-	-	4	1185	26	859	21	100

(cont'd)

Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha N	1000-9999 ha Area	100-999 ha N	100-999 ha Area	10-99 ha N	10-99 ha Area	1-9.9 ha N	1-9.9 ha Area
1	5QB06	1	2366	5	1769	49	1623	39	170
1	5QB07	-	12480	6	2759	9	253	23	82
1	5QB08	8	-	34	10339	167	5102	176	775
1	5QB09	-	-	8	2384	23	718	31	146
1	5QC**	15	51563	107	28084	571	17783	614	2868
1	5QD02	3	4981	47	11973	267	7805	437	1809
1	5QD04	-	-	7	2170	47	1630	42	192
1	5QD05	4	6846	21	6786	112	3327	165	722
1	5QE**	30	78299	167	46501	840	26619	1375	5561
1	5RA**	1	1334	15	4320	133	3844	163	871
1	5RB**	14	25817	90	24118	781	23617	1004	5085
1	5RC**	21	48141	240	72098	1665	48780	1684	7930
1	5RD**	-	-	16	2957	115	3653	101	518
1	5RE**	1	1614	29	9180	208	6317	218	1057
Zone 1 Totals		370	984307	5571	1289291	48136	1210378	83770	376566
2	2AA**	3	7853	17	4643	57	1388	197	607
2	2AB**	6	18468	68	14395	554	15184	1247	4934
2	2AC**	1	4766	42	13183	314	8401	886	3549
2	2AD**	21	50489	202	51704	1501	42055	3552	14275
2	2AE**	-	-	20	3493	180	4588	884	3328
2	2BA**	4	6012	42	9353	406	11175	1998	7371
2	2BB**	2	4303	46	9439	522	13935	1340	5600
2	2BC01	2	7418	22	5876	187	5749	321	1422
2	2BC02	-	-	-	-	7	101	52	178
2	2BC03	-	-	4	540	45	1218	198	790
2	2BC05	-	-	-	-	6	90	85	309
2	2BC11	2	2111	16	4632	180	4825	413	1685
2	4GA14	2	8206	15	2378	94	2206	196	857
2	4GA15	5	14605	21	6076	225	6080	1454	6360
2	4GA16	6	14207	32	8468	254	6435	412	1801
2	4GA17	1	1255	10	2752	102	2610	148	647
2	4GA18	-	-	22	4937	144	3723	249	1089
2	4GB**	27	66479	239	60511	1739	49849	3285	13294
2	4GC08	-	-	2	996	30	698	908	3970
2	4GC09	-	-	3	364	25	728	42	183
2	4GC10	5	10416	19	1538	232	5504	389	1703
2	4GC11	-	-	21	4965	159	3784	162	711
2	4GC12	1	4168	8	4694	52	1072	84	366

(cont'd)

Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha		100-999 ha		10-99 ha		1-9.9 ha	
		N	Area	N	Area	N	Area	N	Area
2	4GC13	-	-	6	1143	59	1335	80	348
2	4GC14	1	2954	24	1295	142	3086	226	991
2	4GD09	1	1255	18	4269	58	1862	73	329
2	4GD10	-	-	4	607	31	840	112	506
2	4GD11	-	-	4	809	39	1629	60	270
2	4GD12	1	1044	7	2428	69	2246	74	337
2	4GD13	1	7042	10	2590	75	2034	121	548
2	4GD14	1	1093	10	2639	59	1781	66	298
2	4GD16	-	-	7	1140	40	945	27	124
2	4GD17	-	-	4	885	56	1750	48	217
2	4GD18	-	-	12	2894	82	2276	78	352
2	4GD19	1	1295	5	1109	38	1032	42	188
2	4GE07	1	1497	6	1312	31	1030	45	149
2	4GE08	-	-	4	499	15	395	24	89
2	4GE09	-	-	2	235	18	536	37	134
2	4GE10	-	-	1	102	11	318	17	76
2	4GE12	-	-	2	745	15	451	53	199
2	4GE13	-	-	3	1022	18	493	53	187
2	4GE14	-	-	13	2935	56	1709	127	462
2	4GE15	3	9853	5	1242	71	1944	144	544
2	4JA01	1	1252	8	2392	157	4079	321	1200
2	4JB**	2	3035	7	1729	87	2541	326	1136
2	4JC**	5	13503	53	11005	479	13057	1447	5632
2	4JD**	9	21529	76	21797	696	19654	2215	9100
2	4JE03	-	-	1	241	1	17	9	20
2	4JE04	-	-	1	108	3	54	21	90
2	4JE05	-	-	1	107	10	244	28	85
2	4JF05	-	-	2	800	24	775	13	55
2	4JF06	-	-	1	304	9	312	17	67
2	4JF07	-	-	1	129	3	47	11	40
2	4JF08	-	-	1	251	10	297	12	66
2	4JF09	-	-	-	-	14	392	18	79
2	4JF10	-	-	2	290	9	307	40	116
2	4JF11	-	-	11	4249	51	1427	111	432
2	4JF12	1	7252	9	2189	79	2263	134	461
2	4JF13	-	-	3	863	20	478	59	237
2	4JF16	-	-	3	507	18	642	40	142
2	4JF17	2	8009	1	550	12	315	36	150
2	4JF18	1	1243	2	549	1	83	8	30
2	4JF19	-	-	7	1137	56	1671	187	643
2	4JF20	1	1936	6	1502	10	359	52	236

(cont'd)

Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha N	Area	100-999 ha N	Area	10-99 ha N	Area	1-9.9 ha N	Area
2	4JF21	-	-	1	231	4	97	26	84
2	4JF22	1	3526	1	797	40	1159	245	812
2	4JF23	1	1295	3	949	11	337	58	200
2	4JF24	-	-	-	-	14	304	80	278
2	4JF25	1	1808	8	3365	39	1054	189	594
2	4JF26	-	-	9	3589	55	1458	159	543
2	4KA**	-	-	9	1255	280	5301	576	2481
2	4LB01	-	-	-	-	22	539	76	246
2	4LB02	-	-	-	-	15	322	41	151
2	4LB03	-	-	1	146	5	120	20	72
2	4LB04	-	-	2	349	37	930	97	335
2	4LB05	-	-	2	525	18	425	44	163
2	4LD**	-	-	7	1991	86	2237	178	720
2	4LF**	2	4495	13	2747	104	3229	277	987
2	4LG**	2	8377	1	151	38	1124	339	1078
2	4LJ01	-	-	3	704	24	454	59	201
2	4LJ05	1	3828	2	321	13	344	42	133
2	4LK**	3	4465	14	4821	125	3492	496	1749
2	4LL**	1	1930	19	6688	130	3813	547	1726
2	4LM**	1	3351	6	1113	19	574	61	193
2	4MA01	-	-	1	219	26	722	125	425
2	4MA02	-	-	1	108	14	419	28	119
2	4MC**	-	-	6	1258	123	3385	351	1258
2	4MD02	-	-	1	174	13	380	27	109
2	4MD03	-	-	-	-	18	378	40	176
2	4ME**	4	14581	40	8901	365	9624	1081	3836
2	4MF**	4	6070	56	8695	570	15591	1083	449
2	4NB**	-	-	23	4532	156	4047	20	229
2	4NC**	4	7770	96	17847	736	19233	1433	6955
2	5PA**	22	54524	192	55668	958	29511	2371	7545
2	5PB**	47	108124	323	80216	1843	54444	3479	13537
2	5PC**	-	-	-	-	8	179	22	83
2	5PD02	-	-	-	-	4	168	6	20
2	5PD03	-	-	-	-	-	-	1	6
2	5PD04	2	2141	11	3212	49	1203	176	569
2	5PD05	3	10567	25	5804	142	4469	282	1034
2	5PD06	3	8666	25	7272	124	3491	221	914
2	5QA**	35	92129	248	65476	1279	38256	1997	8140
2	5QB01	4	7096	63	17660	293	9566	321	1327
2	5QB02	1	1102	12	2320	36	1368	39	155
2	5QB03	3	3873	18	4025	99	2780	99	471

(cont'd)

Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha N	Area	100-999 ha N	Area	10-99 ha N	Area	1-9.9 ha N	Area
2	5QD01	10	27144	44	10731	302	9190	518	2038
2	5QD03	1	2343	7	2378	8	342	32	131
Zone 2 Totals		276	683753	2507	621774	17992	504163	42476	163666
3	2BC04	-	-	-	-	20	321	154	556
3	2BC06	-	-	-	-	18	344	142	403
3	2BC07	-	-	-	-	9	155	105	314
3	2BC08	-	-	3	392	81	1538	605	2057
3	2BC09	-	-	-	-	16	246	121	370
3	2BC10	-	-	1	197	59	1219	238	847
3	2BC12	-	-	3	351	12	281	36	141
3	2BD01	-	-	-	-	28	479	252	0
3	2BD02	2	2932	18	4509	152	3796	564	0
3	2BD03	-	-	-	-	7	168	114	0
3	2BD04	-	-	1	146	16	312	154	0
3	2BD05	2	5365	16	2723	342	8788	714	0
3	2BD06	4	14005	24	6709	281	7734	946	0
3	2BD10	1	1226	6	1779	56	1397	175	0
3	2CE10	-	-	2	312	76	2413	167	724
3	2JC**	2	4915	24	7655	146	4492	379	1352
3	2JD06	-	-	4	803	36	1003	143	552
3	2JD08	2	2627	15	4615	177	4410	516	2085
3	2JD09	-	-	3	700	29	735	59	274
3	2JD10	1	1131	2	479	25	671	85	338
3	4JA02	2	12648	7	1149	135	3851	200	948
3	4JA03	-	-	1	113	26	789	59	240
3	4JA04	1	1295	-	-	24	599	82	278
3	4LA**	5	10994	72	20039	612	16045	1622	6131
3	4LB06	-	-	-	-	2	33	9	38
3	4LB07	-	-	-	-	2	44	3	13
3	4LB08	-	-	-	-	4	60	32	118
3	4LB09	-	-	2	928	32	1019	63	255
3	4LB10	-	-	7	1778	54	1569	124	446
3	4LC**	5	12896	80	18867	792	21095	2225	9036
3	4LE01	1	1828	6	1940	44	1129	117	438
3	4LE04	-	-	6	1238	44	1305	176	682
3	4LE06	1	1263	1	210	6	222	25	87
3	4LE07	1	1890	6	1293	46	1031	150	582
3	4LE08	-	-	4	606	31	776	89	389

(cont'd)

Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha N	1000-9999 ha Area	100-999 ha N	100-999 ha Area	10-99 ha N	10-99 ha Area	1-9.9 ha N	1-9.9 ha Area
3	4LE09	-	-	4	1601	50	1387	104	405
3	4LE10	-	-	2	297	18	382	60	235
3	4LE11	-	-	-	-	3	91	7	42
3	4LH**	2	10037	22	4544	241	6579	788	3234
3	4LJ02	-	-	-	-	3	66	16	47
3	4LJ03	-	-	1	108	5	108	13	58
3	4LJ04	-	-	9	1494	44	1201	122	541
3	4MA03	-	-	1	142	4	150	11	32
3	4MA04	-	-	-	-	5	118	23	69
3	4MA05	-	-	5	1301	17	705	33	118
3	4MB**	1	2165	13	2413	146	3794	406	1544
3	4MD01	2	13708	1	158	50	1520	215	888
3	4MD04	-	-	2	446	10	342	18	69
3	4MD05	-	-	2	360	27	709	107	427
3	4MD06	-	-	3	957	53	1399	187	779
3	4MD07	-	-	2	315	11	206	43	149
3	4MD08	-	-	2	456	28	673	64	218
Zone 3 Totals		35	100925	383	94123	4155	109499	12862	38599
4	2BD07	1	1127	5	1368	36	1027	164	629
4	2BD08	-	-	8	1751	71	2350	358	1326
4	2BD09	3	6840	10	2477	115	2870	254	1048
4	2BE**	-	-	31	6196	608	14719	2434	9396
4	2BF**	-	-	33	5580	536	12721	2157	8721
4	2CA01	-	-	3	1081	16	425	42	138
4	2CA02	1	2254	5	1616	115	2492	471	1860
4	2CA03	1	1149	4	803	29	683	151	695
4	2CA04	-	-	3	652	8	208	14	55
4	2CB**	4	11540	48	12648	784	19679	2107	8799
4	2CC02	-	-	4	957	87	1881	362	1466
4	2CC04	1	2707	1	127	18	363	13	62
4	2CC05	-	-	9	2359	107	2788	308	1160
4	2CC06	-	-	6	1798	53	1347	74	732
4	2CC07	-	-	2	681	47	1018	187	985
4	2CC08	1	2469	3	906	40	981	111	451
4	2CC09	1	1098	6	1102	69	1875	251	1916
4	2CC10	-	-	1	125	18	397	97	316
4	2CE03	1	1162	8	1654	131	3217	425	1873

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Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha N	Area	100-999 ha N	Area	10-99 ha N	Area	1-9.9 ha N	Area
4	2CE06	-	-	7	1344	172	3532	668	2941
4	2CE09	-	-	5	665	64	1617	192	853
4	2JE15	1	2106	17	4780	125	3534	321	1255
4	2JE16	-	-	2	325	8	295	19	65
4	2JE27	-	-	-	-	4	100	6	13
4	2KC01	4	9105	1	761	6	125	16	81
4	2KC05	1	1202	1	110	4	143	6	21
4	2KC07	1	1467	1	531	7	178	13	66
4	2KE01	2	4755	3	1030	41	1233	166	620
4	2KE02	1	2356	-	-	7	246	27	107
4	2LA01	-	-	-	-	-	-	2	11
4	2LA02	-	-	-	-	4	138	8	12
4	2LA03	-	-	-	-	1	24	5	13
4	2LA05	-	-	2	376	2	36	4	16
4	2LA06	-	-	3	837	1	19	6	23
4	2LA07	2	7841	4	1810	20	658	23	87
4	2LB**	1	1068	-	-	5	146	27	87
4	2MA08	-	-	7	2512	7	225	3	15
4	2MA09	1	2517	5	919	5	189	5	24
4	2MB**	-	-	-	-	2	143	39	90
4	2MC**	-	-	1	346	3	95	10	32
4	4LE02	1	1041	2	1275	16	517	70	273
4	4LE03	-	-	-	-	11	329	32	123
4	4LE05	1	1599	2	288	20	512	77	278
Zone 4 Totals		30	65403	253	61790	3423	85075	11725	48734
5	2CA05	-	-	2	571	3	100	5	11
5	2CA06	-	-	-	-	2	40	4	11
5	2CA07	-	-	-	-	-	-	4	11
5	2CA08	-	-	-	-	2	31	7	23
5	2CA09	-	-	-	-	3	94	5	19
5	2CA10	-	-	-	-	-	-	1	3
5	2CA11	1	1029	10	2639	70	1927	260	1325
5	2CA12	-	-	-	-	-	-	3	11
5	2CC01	-	-	-	-	2	83	6	18
5	2CC03	1	1189	4	685	1	19	-	0
5	2CD01	-	-	-	-	6	182	10	48
5	2CD02	2	3156	25	7120	126	3254	351	1405
5	2CD03	-	-	7	1365	17	675	13	56

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Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha		100-999 ha		10-99 ha		1-9.9 ha	
		N	Area	N	Area	N	Area	N	Area
5	2CD04	-	-	2	259	16	374	23	84
5	2CD05	1	2242	2	215	11	258	21	104
5	2CD06	-	-	4	1159	4	175	23	149
5	2CD08	2	14701	13	3847	76	2355	120	541
5	2CD09	-	-	1	225	9	357	18	80
5	2CD10	-	-	-	-	1	20	-	0
5	2CE01	1	1144	4	747	19	576	34	127
5	2CE11	-	-	-	-	-	-	2	11
5	2CF04	-	-	2	1184	16	522	52	226
5	2CF06	-	-	5	750	8	223	19	78
5	2CF17	-	-	-	-	1	13	6	27
5	2CG**	3	11693	26	6320	82	2125	194	656
5	2DC03	-	-	-	-	1	32	1	4
5	2DC05	-	-	1	147	6	160	18	62
5	2DD**	3	3526	42	11359	352	9330	892	3687
5	2EA**	5	7780	69	18245	407	11869	960	4082
5	2EB**	7	25397	77	19343	556	14854	1169	5418
5	2EC**	6	11256	22	5583	193	5213	716	2681
5	2ED01	-	-	-	-	2	142	-	0
5	2ED02	-	-	2	255	4	99	1	4
5	2ED03	-	-	2	482	-	-	2	7
5	2ED04	-	-	-	-	-	-	1	10
5	2ED05	-	-	-	-	-	-	3	5
5	2ED06	-	-	1	542	-	-	2	2
5	2ED07	-	-	1	159	28	712	58	294
5	2ED08	-	-	-	-	-	-	3	5
5	2ED16	-	-	-	-	-	-	1	2
5	2HD**	-	-	-	-	2	22	35	83
5	2HE**	2	3108	4	1124	3	244	13	35
5	2HF**	5	9532	53	15685	257	7195	630	2566
5	2HG**	1	8262	-	-	1	23	33	78
5	2HH**	8	21655	22	7552	169	4226	548	2299
5	2HJ**	-	-	-	-	5	178	47	144
5	2HK**	1	1387	28	9774	126	3392	297	1115
5	2HL**	1	1225	9	3164	64	1692	295	1088
5	2HM**	-	-	18	5509	69	1909	166	646
5	2JE01	1	1653	3	364	53	1751	218	841
5	2JE02	2	4569	3	515	29	834	55	225
5	2JE03	-	-	2	319	12	457	36	154
5	2JE04	3	3914	10	2940	120	3339	318	1489
5	2JE05	-	-	2	359	8	212	22	95
5	2JE06	-	-	-	-	5	83	14	69

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Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha N	Area	100-999 ha N	Area	10-99 ha N	Area	1-9.9 ha N	Area
5	2JE07	1	1708	-	-	8	246	13	41
5	2JE08	-	-	-	-	26	642	81	312
5	2JE09	-	-	-	-	4	125	20	81
5	2JE12	-	-	8	1294	62	1789	126	571
5	2JE13	-	-	6	881	19	392	52	219
5	2JE14	-	-	2	234	28	799	121	465
5	2KA**	2	11230	9	1612	117	2839	273	1176
5	2KB**	5	8441	48	14389	322	8532	1623	5872
5	2KC02	2	6449	6	1200	67	1688	392	1376
5	2KC06	-	-	1	151	28	647	66	267
5	2KC08	1	1730	-	-	5	99	12	44
5	2KC09	-	-	1	146	3	109	14	47
5	2KC10	-	-	2	814	7	234	25	93
5	2KD**	6	17486	63	16616	402	11617	1311	4837
5	2KE03	-	-	1	611	12	280	46	180
5	2KE04	-	-	2	252	11	334	43	168
5	2KE05	-	-	6	1459	16	468	40	151
5	2KE06	-	-	-	-	10	233	49	196
5	2KE07	-	-	-	-	4	179	29	129
5	2KF**	5	13326	32	9021	153	4436	468	1930
5	2LA08	-	-	1	625	7	163	3	10
5	2LA09	-	-	2	585	2	79	4	12
5	2LA10	1	2449	7	2172	19	580	40	163
5	2MA01	-	-	-	-	1	16	-	0
5	2MA06	2	2678	28	8342	67	2111	77	360
5	2MA07	1	1803	1	136	6	203	9	53
Zone 5 Totals		85	205718	704	191046	4353	120211	12672	50967
6	2ED09	-	-	-	-	2	110	12	34
6	2ED10	-	-	-	-	1	12	4	8
6	2ED11	-	-	-	-	2	36	6	15
6	2ED12	-	-	-	-	-	-	8	21
6	2ED13	-	-	-	-	1	48	4	12
6	2ED14	-	-	1	188	-	-	1	2
6	2ED15	-	-	-	-	-	-	4	16
6	2FA**	-	-	17	3983	43	1529	59	240
6	2FB**	-	-	1	723	13	348	17	54
6	2FC**	-	-	-	-	34	887	102	376
6	2FD**	-	-	-	-	3	38	13	39

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Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha N	1000-9999 ha Area	100-999 ha N	100-999 ha Area	10-99 ha N	10-99 ha Area	1-9.9 ha N	1-9.9 ha Area
6	2FE**	-	-	-	-	6	128	15	41
6	2FF**	-	-	1	217	-	-	12	37
6	2GA**	1	1242	3	1441	12	208	101	347
6	2GB**	-	-	-	-	12	178	62	170
6	2GC**	-	-	-	-	19	444	121	378
6	2GD**	-	-	3	1700	5	71	56	118
6	2GE**	-	-	-	-	2	23	18	66
6	2GF**	-	-	-	-	-	-	2	14
6	2GG**	-	-	1	421	8	223	70	188
6	2GH**	-	-	1	145	13	298	38	141
6	2HA**	-	-	2	439	10	338	55	136
6	2HB**	-	-	3	507	7	205	118	362
6	2HC**	-	-	-	-	13	246	174	394
Zone 6 Totals		1	1242	33	9764	206	5370	1072	3209
7	2CD07	-	-	5	1529	27	557	72	284
7	2CE02	7	22835	36	8755	426	10585	1126	5087
7	2CE04	1	1117	-	-	19	415	30	113
7	2CE05	-	-	3	854	30	655	142	638
7	2CE07	-	-	3	937	37	744	125	591
7	2CE08	2	2471	11	1922	70	1736	225	976
7	2CF01	-	-	-	-	8	168	17	57
7	2CF02	-	-	1	250	1	10	4	14
7	2CF03	1	1142	12	2757	56	1319	133	580
7	2CF05	1	8337	27	6849	87	2558	105	543
7	2CF07	1	1078	10	3159	108	2996	347	1492
7	2CF08	-	-	11	2810	16	410	24	104
7	2CF09	-	-	2	806	5	182	12	63
7	2CF10	-	-	3	939	22	667	102	428
7	2CF11	-	-	2	570	4	77	4	29
7	2CF12	-	-	-	-	11	233	81	361
7	2CF13	-	-	1	316	15	362	126	533
7	2CF14	-	-	1	184	11	239	55	241
7	2CF15	-	-	5	849	13	280	123	507
7	2CF16	2	5846	26	5969	288	7665	853	3697
7	2DA**	2	2053	21	3577	255	6386	931	3593
7	2DB**	-	-	8	1180	53	1447	146	582
7	2DC01	-	-	23	519	172	4589	595	2361
7	2DC02	4	6071	10	2645	93	2440	195	832
7	2DC04	1	1819	6	2238	26	745	87	338

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Appendix D: (Cont'd)

Zone	Wshed	1000-9999 ha		100-999 ha		10-99 ha		1-9.9 ha	
		N	Area	N	Area	N	Area	N	Area
7	2DC06	4	6987	16	4495	181	5317	583	2391
7	2DC07	2	2321	7	1315	57	1512	105	425
7	2DC08	1	3189	7	1754	50	1235	206	884
7	2DC09	-	-	4	728	51	1328	109	431
7	2JD01	1	1455	15	3046	123	3528	330	1326
7	2JD02	1	6263	7	1862	50	1543	129	547
7	2JD03	1	1006	8	2346	108	3025	279	1088
7	2JD04	1	2129	3	1024	35	912	85	386
7	2JD05	-	-	-	-	19	646	54	187
7	2JD07	1	1046	10	3261	67	1915	168	683
Zone 7 Totals		34	77165	304	69445	2594	68426	7708	32392